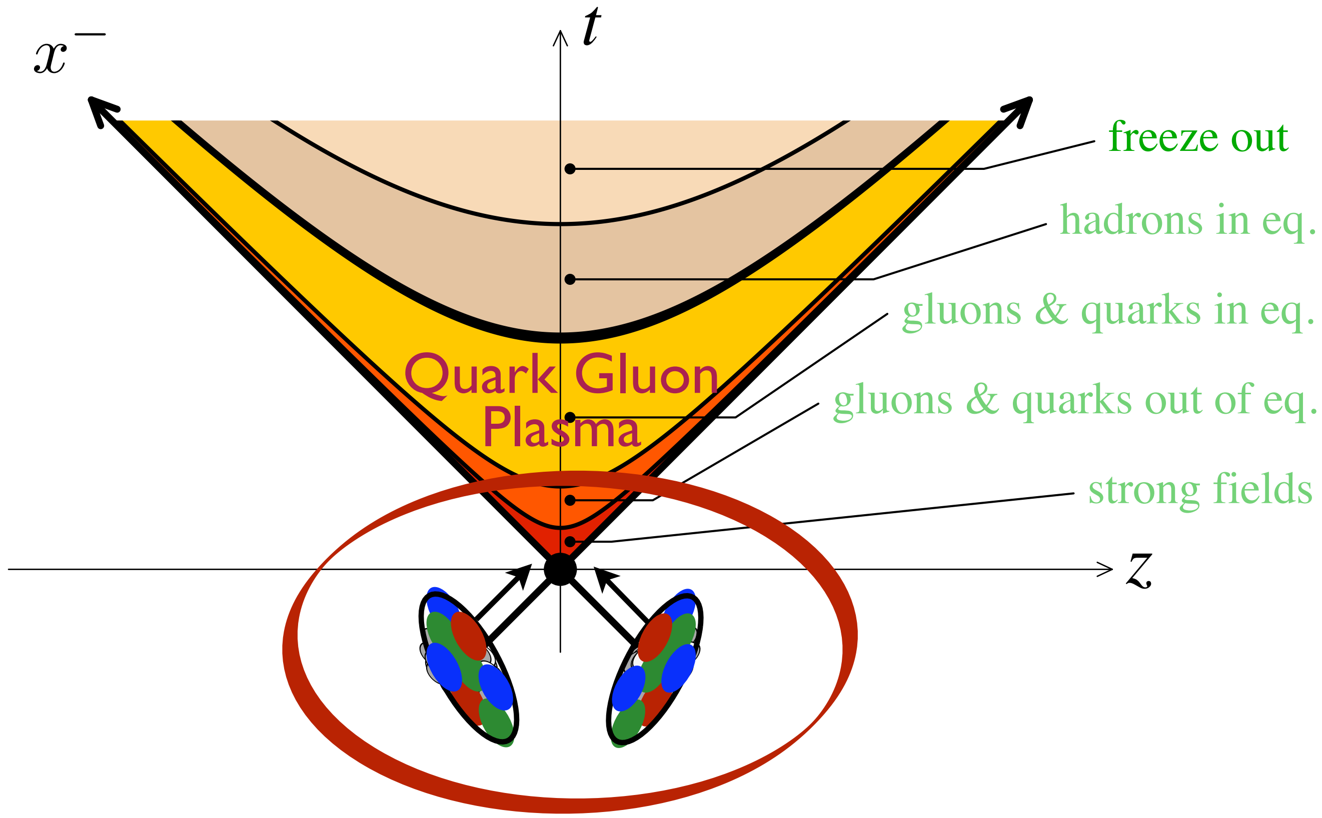
Color Glass Condensate and implications for the LHC

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
34th Course
Probing the Extremes of Matter with Heavy Ions
Erice-Sicily: 16 - 24 September 2012

Javier L Albacete

OUTLINE



This talk: Initial conditions for heavy ion collisions

1.- What is the quark gluon content of the colliding nuclei?

2.- Is it just a simple addition of the quarks/gluons in their constituent nucleons

3.- How are these quarks/gluons released during the collision process to
   a) form the Quark Gluon Plasma?
   b) emerge as hard probes of the QGP?

4.- How to test the CGC formalism in the upcoming p+Pb collisions at the LHC

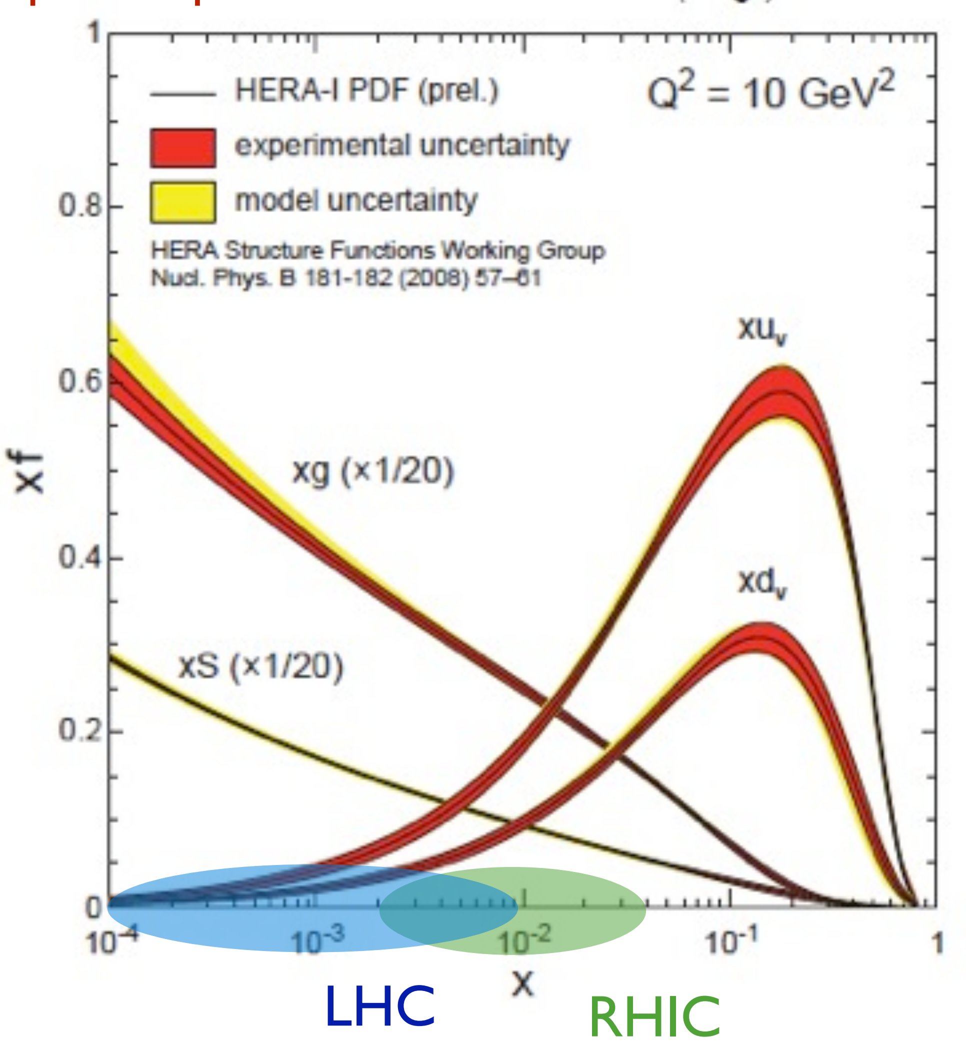
Why small-x matters

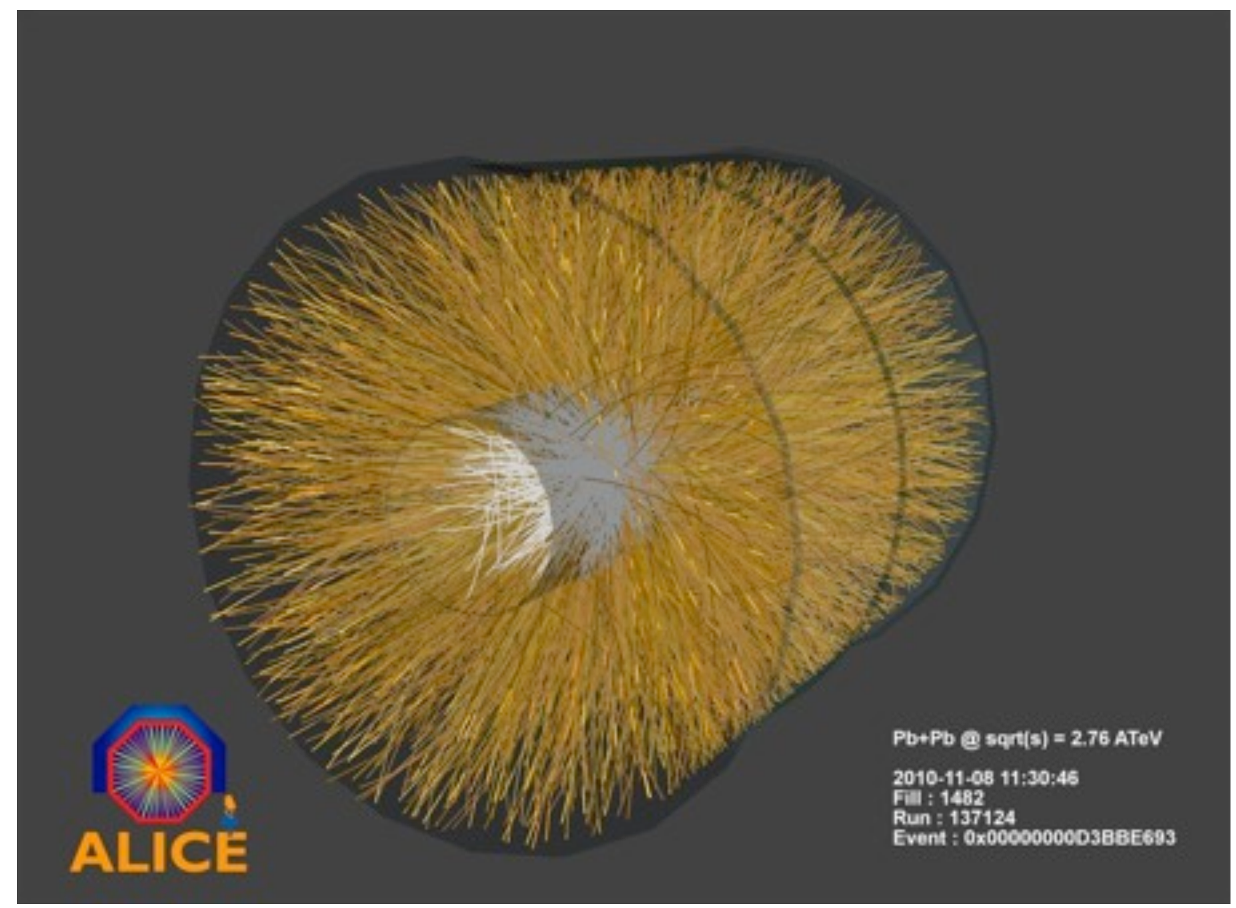
- **x**: fraction of longitudinal momentum carried by a parton inside a hadron. $\mathbf{x = \frac{k_z}{P_z}}$
- ~99% of hadrons produced in high-energy HIC originate from small-x gluons in the colliding nuclei

$$\mathbf{p_\perp \lesssim 2\,\mathrm{GeV} \longrightarrow x_{1,2} \sim \frac{p_\perp}{\sqrt{s}}\, e^{\pm y}}$$

s: collision energy
pt: transverse momentum
y: rapidity

proton pdf's extracted from HERA DIS data





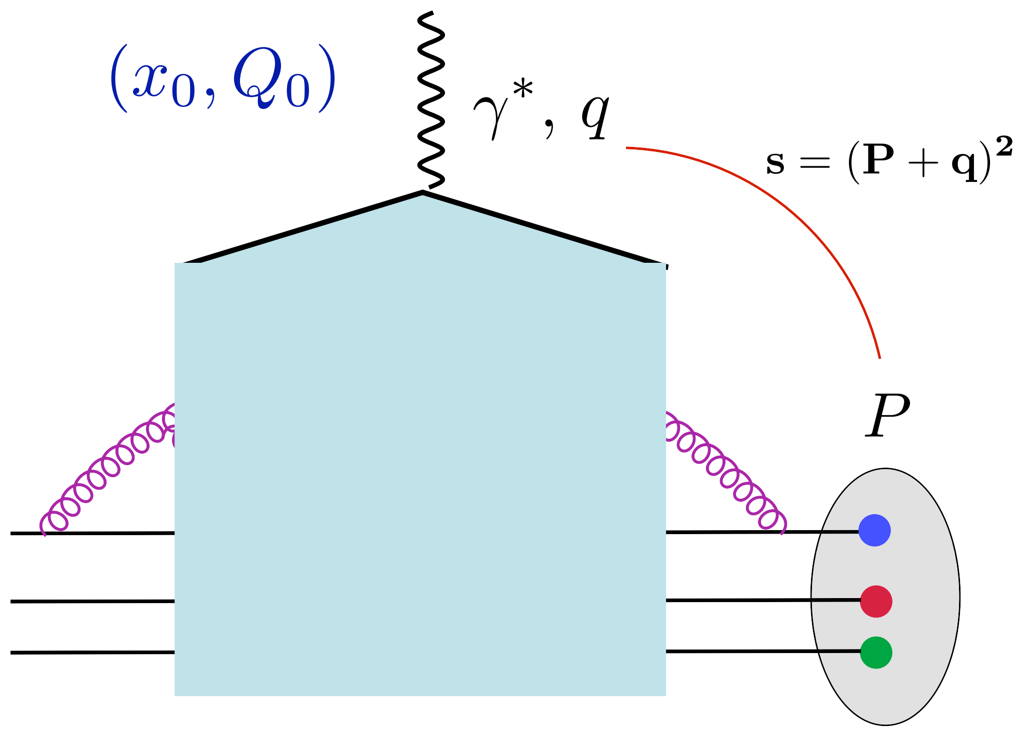
$$\mathbf{x_{RHIC} \sim 10^{-2}} (\sqrt{s} = 200\,\mathrm{GeV})$$

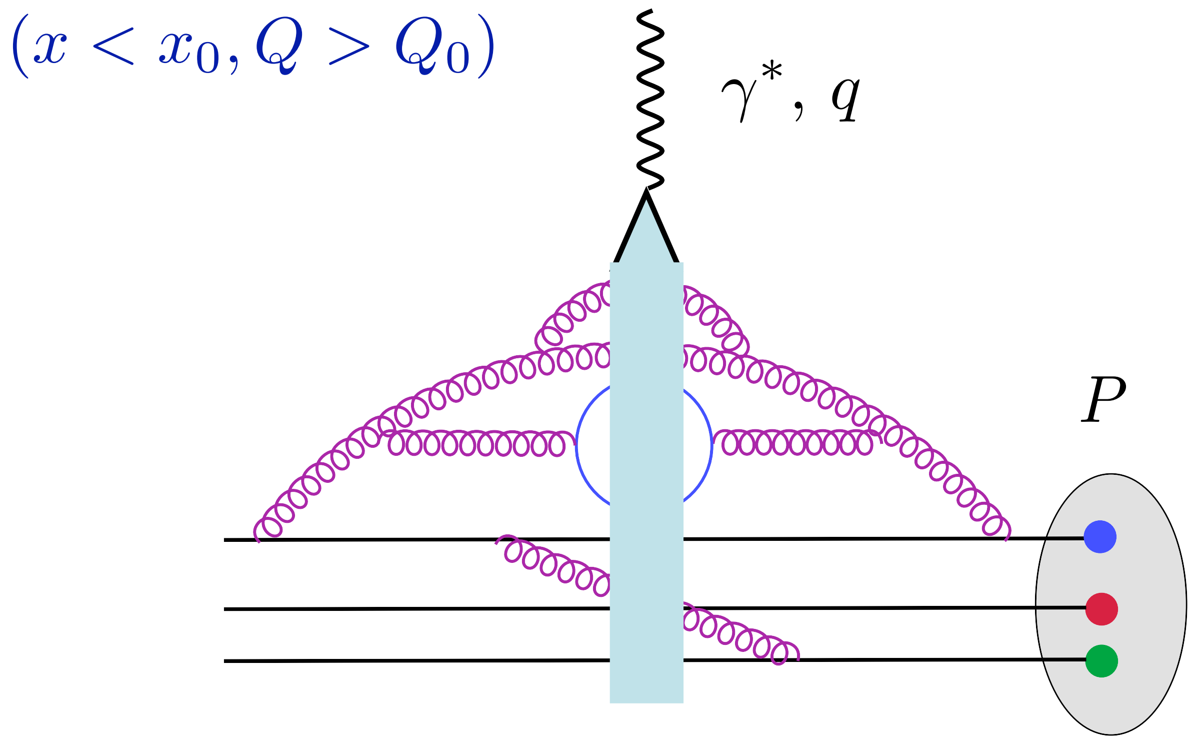
$$\mathbf{x_{LHC} \sim 5 \cdot 10^{-4}} (\sqrt{s} = 2.76\,\mathrm{TeV})$$

Deep Inelastic Scattering: A microscope for hadrons and nuclei

$\mathbf{Q^2 = -q^2}$ transverse resolution: $\Longrightarrow \Delta r_\perp \sim \frac{1}{Q}$

$\mathbf{x \simeq \frac{Q^2}{s}}$ time resolution: $\Longrightarrow \Delta t \sim \frac{2xP}{Q^2}$

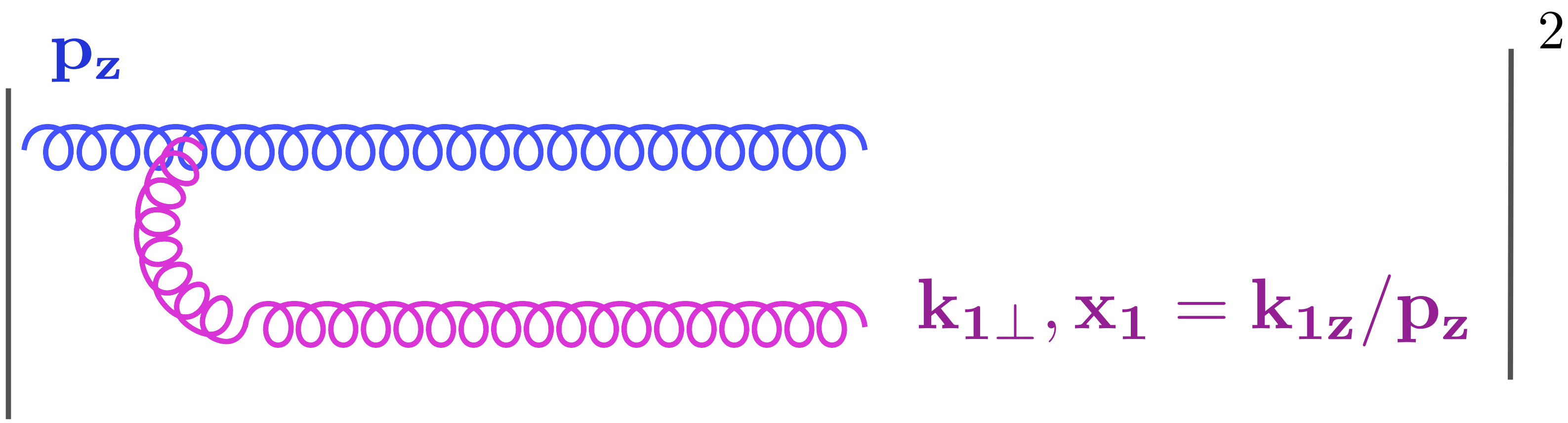




- We do not know (yet) how to derive hadron structure from first principles
- We can (and need!), though, calculate its change with resolution scale by perturbative methods

QCD evolution equations

$$\mathbf{dP_{q/g\to g}} = \frac{\alpha_s\, \mathbf{C_{F/A}}}{\pi}\, \frac{\mathbf{dx}}{\mathbf{x}}\, \frac{\mathbf{d^2k_\perp}}{\mathbf{k_\perp^2}}$$

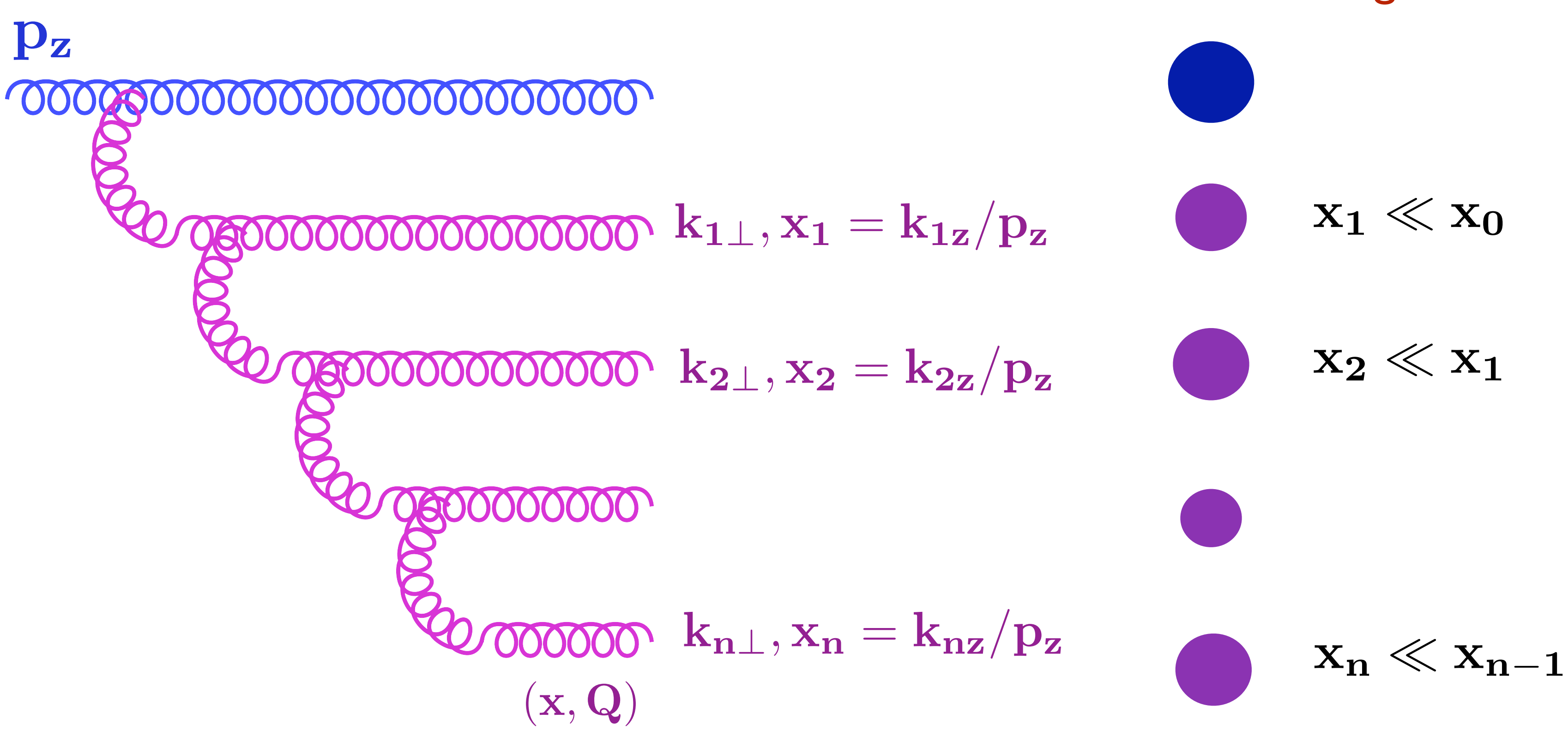


- Probability of emitting one soft gluon: $\mathcal{P}(\mathbf{1}) \sim \alpha_s \ln\left(\frac{\mathbf{x_0}}{\mathbf{x_1}}\right)$

QCD evolution equations

$$\mathbf{dP_{q/g\to g}} = \frac{\alpha_s \mathbf{C_{F/A}}}{\pi} \frac{\mathbf{dx}}{\mathbf{x}} \frac{\mathbf{d^2k_\perp}}{\mathbf{k_\perp^2}}$$

BFKL (x→0)
longitudinal momentum ordering



$$\mathbf{\Delta r_\perp} \sim \mathbf{1/k_t} \sim \mathrm{const}$$

$$\mathbf{\Delta t} \sim (\mathbf{2xP/k_\perp^2}) \sim\to \mathbf{0}$$

"in a BFKL ladder newly emitted gluons are shorter lived and of similar size as the previous ones"

- Probability of emitting n gluons enhanced by large logarithms:

$$\mathcal{P}(\mathbf{n}) \sim \frac{\mathbf{1}}{\mathbf{n!}} \left(\alpha_s \ln\left(\frac{\mathbf{x_0}}{\mathbf{x}}\right)\right)^{\mathbf{n}}$$

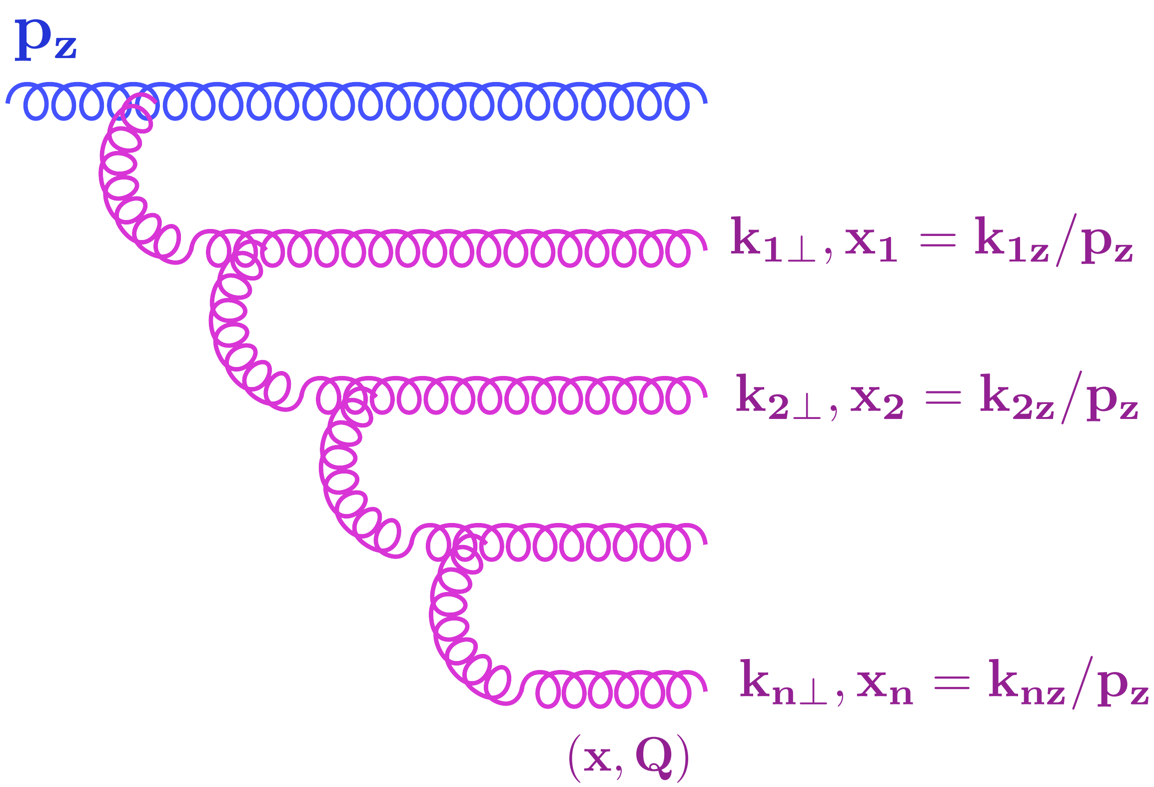
- QCD evolution equations resum large logarithmic contributions to all orders:

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_\perp})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_\perp})$$

"BFKL eqn"

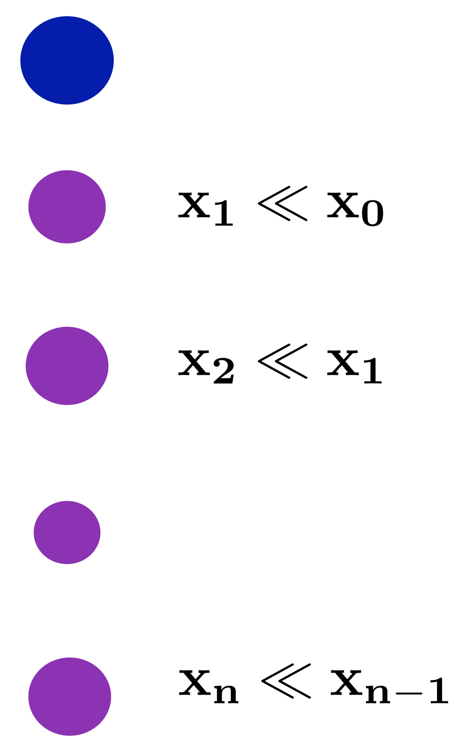
QCD evolution equations

$$dP_{q/g\to g} = \frac{\alpha_s C_{F/A}}{\pi} \frac{dx}{x} \frac{d^2k_\perp}{k_\perp^2}$$



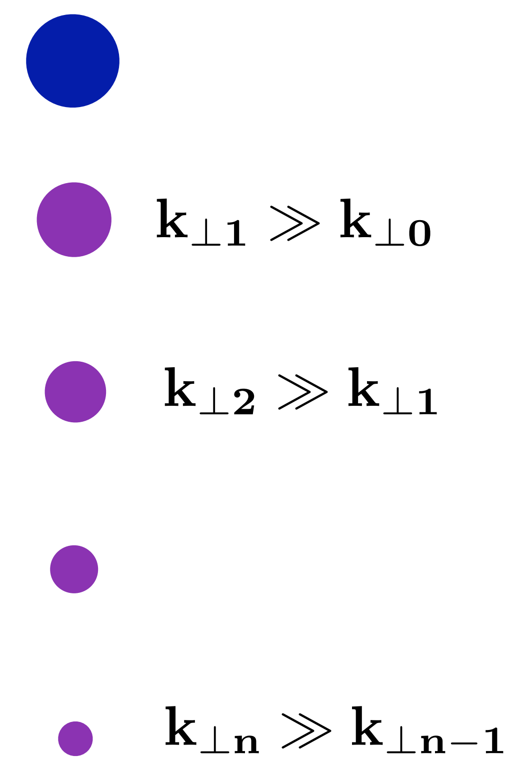
BFKL ($x \to 0$)

longitudinal momentum ordering



DGLAP ($Q^2 \to \infty$)

transverse momentum ordering



- Probability of emitting n gluons enhanced by large logarithms:

$$\mathcal{P}(n) \sim \frac{1}{n!}\left(\alpha_s \ln\left(\frac{x_0}{x}\right)\right)^n \qquad \mathcal{P}(n) \sim \frac{1}{n!}\left(\alpha_s \ln\left(\frac{Q^2}{Q_0^2}\right)\right)^n$$

- QCD evolution equations resum large logarithmic contributions to all orders:

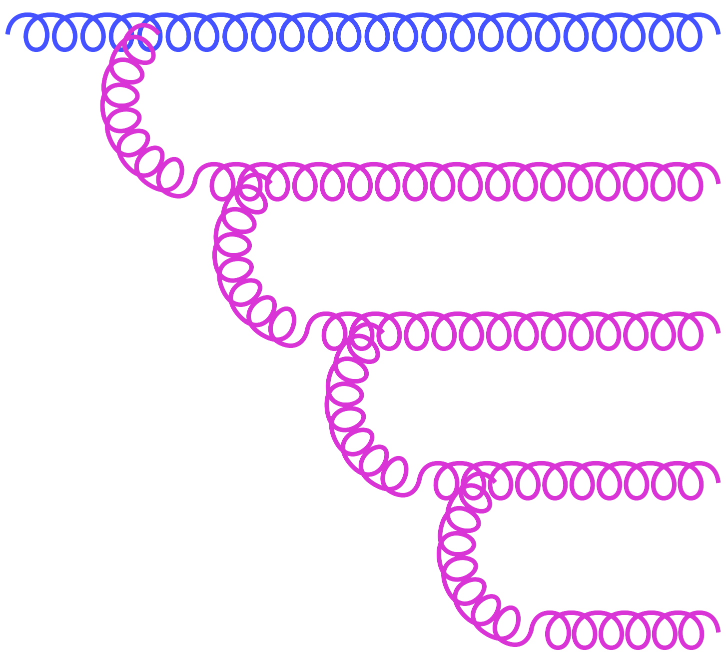
$$\frac{\partial \phi(x, k_\perp)}{\partial \ln(x_0/x)} \approx \mathcal{K} \otimes \phi(x, k_\perp) \qquad \frac{\partial xG(x, Q^2)}{\partial \ln(Q^2/Q_0^2)} \approx P_{gg} \otimes xG(x, Q^2)$$

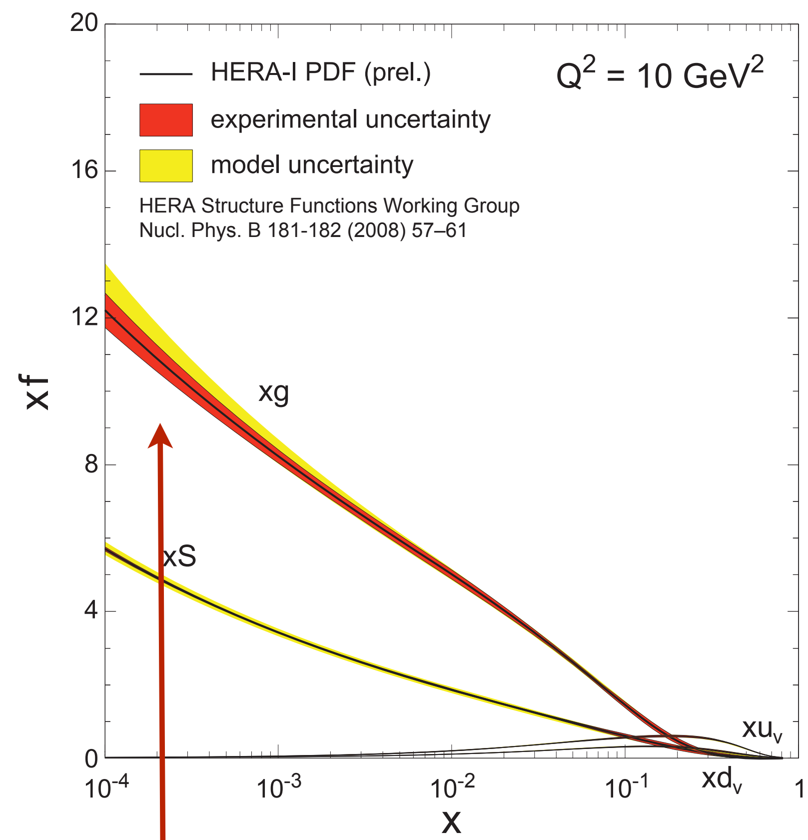
"BFKL eqn" "DGLAP eqn"

Unintegrated gluon distribution: $\phi(x, k_\perp) = \dfrac{dN^g}{d\ln(x_0/x)\, d^2k_\perp}$ $\qquad xG(x, Q^2) = \int^Q d^2k_\perp \phi(x, k_\perp)$

QCD evolution equations

- Both DGLAP and BFKL are LINEAR evolution equations





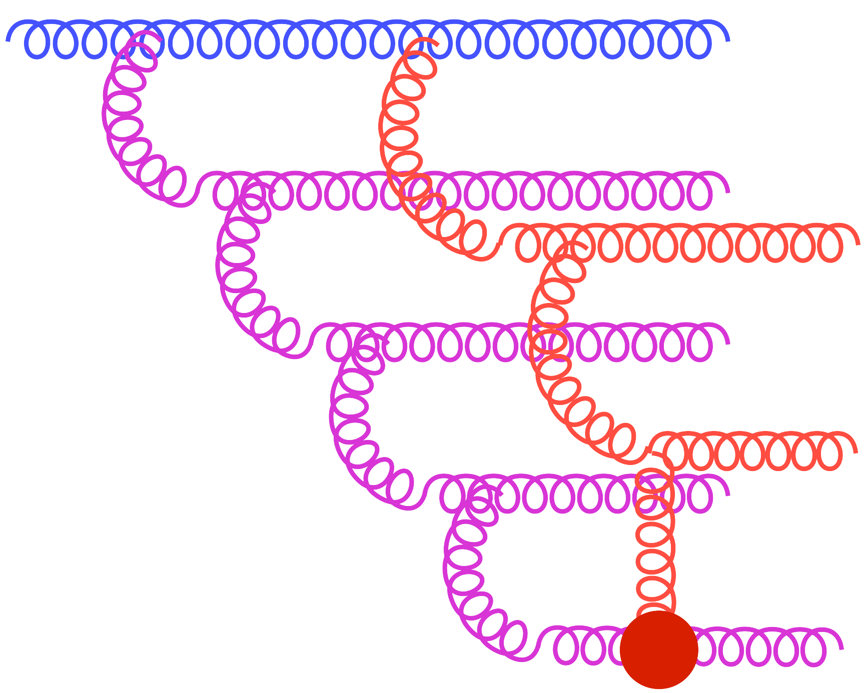
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k}_\perp)}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k}_\perp) \longrightarrow \phi_{\mathbf{BFKL}} \sim \mathbf{x}^{-\alpha_s\,\omega}$$

"BFKL eqn"

"exponential" growth of the gluon distributions at small-x

QCD evolution equations

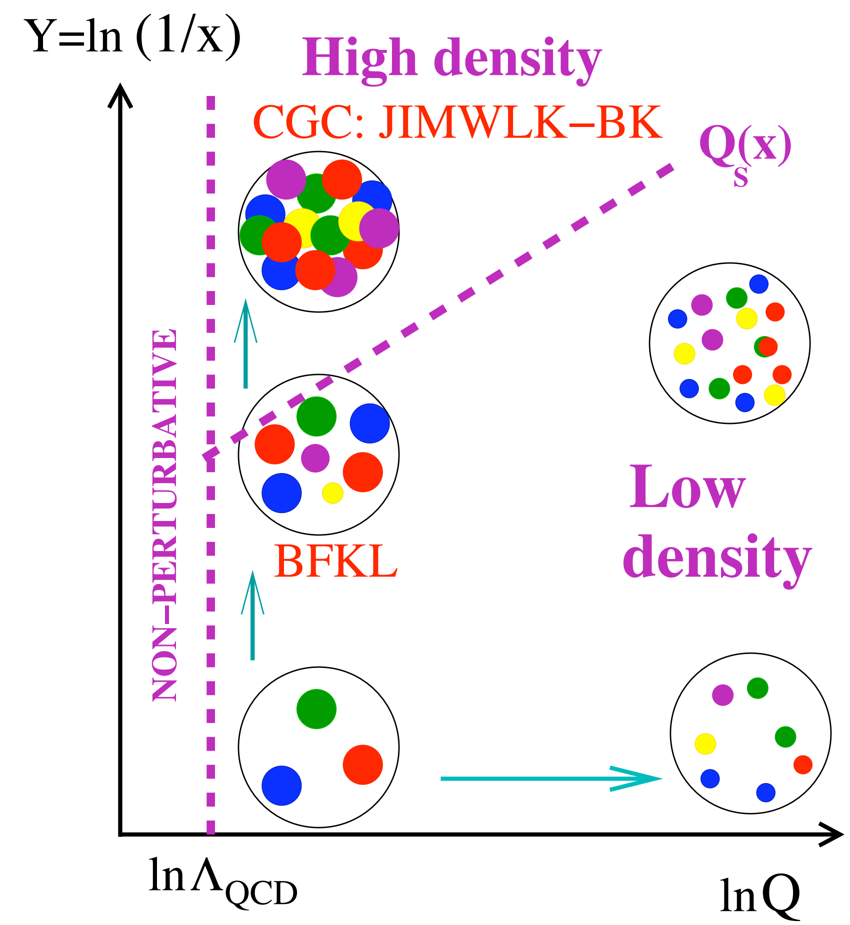
- Both DGLAP and BFKL are LINEAR evolution equations
- At very small-x NON-LINEAR, gluon recombination terms become equally important



$$\frac{\partial \phi(\mathbf{x}, \mathbf{k}_\perp)}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k}_\perp) - \phi(\mathbf{x}, \mathbf{k}_\perp)^2$$

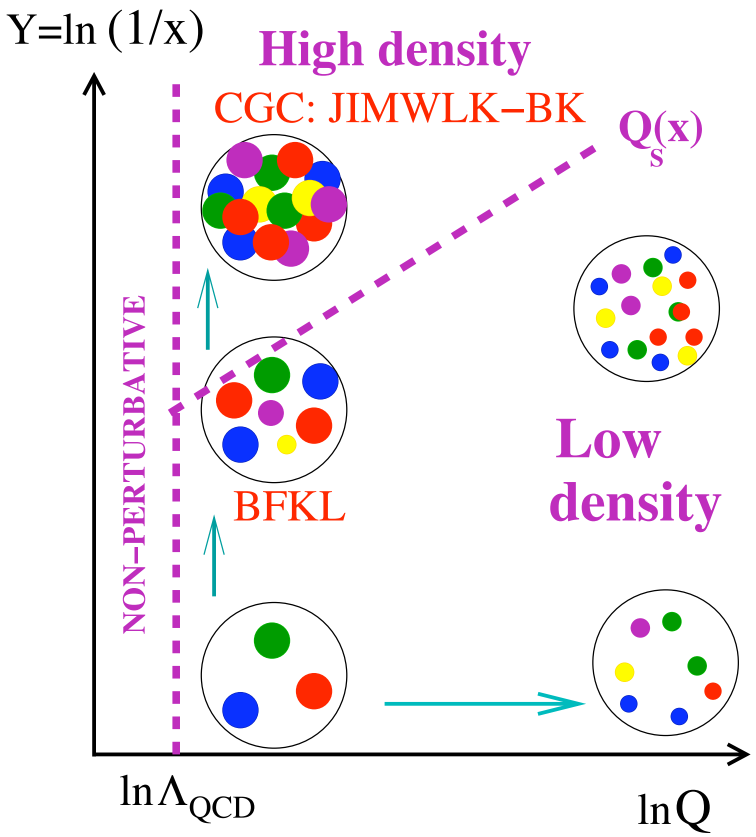
radiation recombination

"BK-JIMWLK eqns"

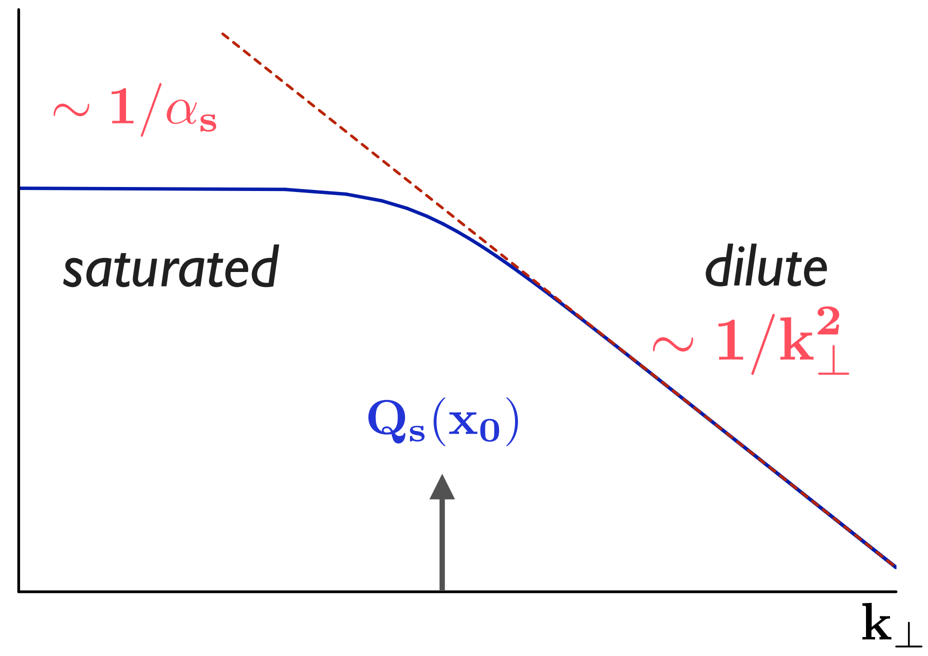


- **Saturation scale:** Transverse momentum scale that determines the onset of non-linear corrections in QCD evolution equations

The saturation regime



$$\phi(\mathbf{x},\mathbf{k}_\perp)=\frac{\mathbf{dN^g}}{\mathbf{dyd^2k_\perp}}\sim\langle\mathcal{A}\,\mathcal{A}\rangle$$



- The saturation domain is characterized by strong color fields: $\phi(\mathbf{x},\mathbf{k}_\perp\lesssim\mathbf{Q_s}(\mathbf{x}))\sim\frac{1}{\alpha_s}\implies\mathcal{A}\sim\frac{1}{g}$
- The saturation scale is enhanced in nuclei due to larger *ab initio* gluon densities: $Q_s^2\sim A^{1/3}\left(\frac{1}{x}\right)^{0.2\div0.3}$
- IF $Q_s^2(x)\gg\Lambda_{QCD}$ then perturbative techniques are applicable in that domain:

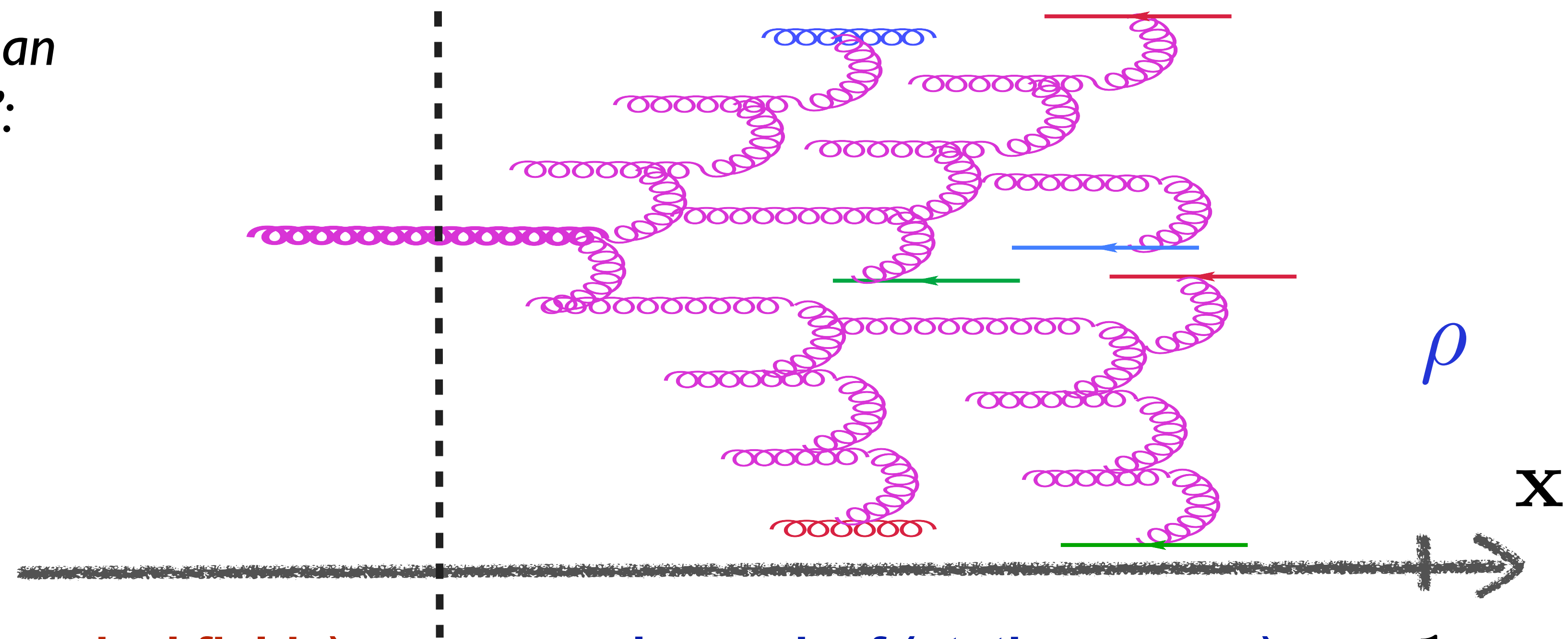
$$Q_s^{Pb}(\mathrm{LHC})\sim 1.5\div 4\,\mathrm{GeV}$$

The Color Glass Condensate (CGC)

- The CGC is an effective theory for the description of high-energy scattering in QCD

"wave function of an energetic nucleus":

$\mathcal{A}^\mu$



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small-x d.o.f (dynamical fields) $\mathbf{x_0}$ **valence d.o.f (static sources)**

$$[\mathbf{D}_\mu, \mathcal{F}^{\mu\nu}] = \mathbf{J}^\nu \qquad \mathcal{L}_{\mathbf{eff}} = -\frac{\mathbf{1}}{\mathbf{4}}\mathcal{F}^{\mathbf{2}} + \mathbf{J} \cdot \mathcal{A} \qquad \mathbf{J}^\nu = \rho(\mathbf{x}_\perp)\delta(\mathbf{x}_-)\delta^{+\nu}$$

- Solutions of classical EOM

- Eikonal (recoil-less) coupling to dynamical fields
- Treated as a random variable with a probability density

$$\mathbf{W}_{\mathbf{x_0}}[\rho(\mathbf{x}_\perp)]$$

The Color Glass Condensate (CGC)

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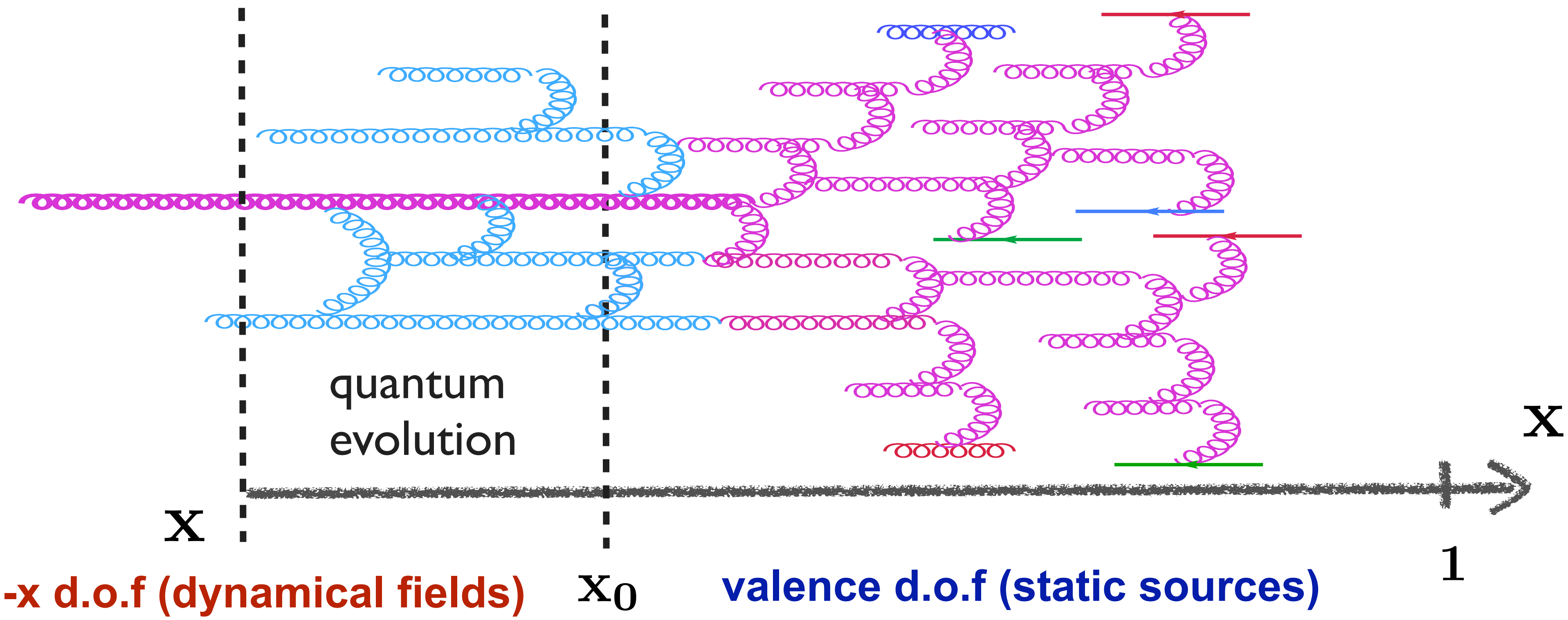


$$[\mathbf{D}_\mu, \mathcal{F}^{\mu\nu}] = \mathbf{J}^\nu \qquad \mathcal{L}_{\mathbf{eff}} = -\frac{1}{4}\mathcal{F}^2 + \mathbf{J}\cdot\mathcal{A} \qquad \mathbf{J}^\nu = \rho(\mathbf{x}_\perp)\delta(\mathbf{x}_-)\delta^{+\nu}$$

- Solutions of classical EOM
- Observables:

$$\langle \mathcal{O}(\mathcal{A})\rangle_x \equiv \int [D\rho]\, W_x[\rho]\, \mathcal{O}(\mathcal{A})$$

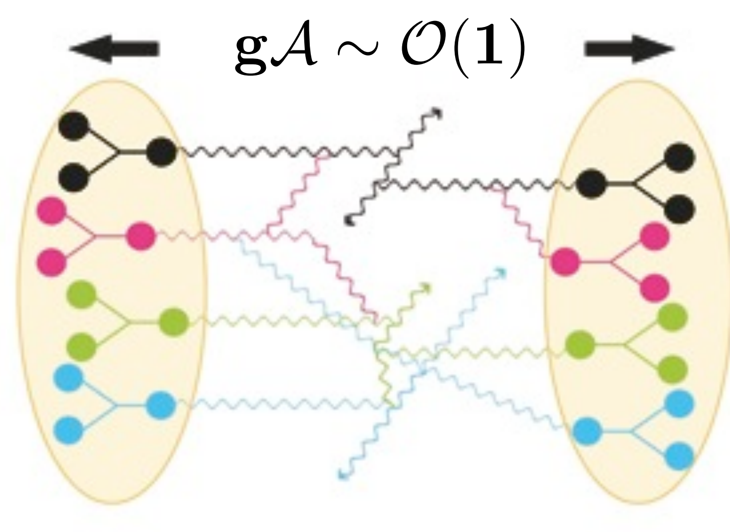
- Eikonal (recoil-less) coupling to dynamical fields
- Treated as a random variable with a probability density

$$\mathbf{W}_{\mathbf{x_0}}[\rho(\mathbf{x}_\perp)]$$

- JIMWLK eqns: Quantum non-linear evolution

$$\frac{\partial \mathbf{W}[\rho]}{\partial \ln(\mathbf{x_0}/\mathbf{x})} = \mathcal{H}^{\mathrm{JIMWLK}}\, \mathbf{W}[\rho]$$

Coherence phenomena in initial particle production. CGC and other approaches



Wave function: Reduced number of scattering centers (gluons) in the wave function of colliding nuclei

-CGC: Saturation + non-linear evolution $$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$ radiation recombination $\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$

-Other approaches: nuclear shadowing, string fusion, percolation, energy dependent intrinsic transverse momentum...

Initial particle production: Rearrangement of perturbation series due to the presence of strong color fields

-CGC: Resummation of terms $\mathbf{g}\mathcal{A} \sim \mathcal{O}(\mathbf{1})$ - Classical Yang-Mills EOM: $[\mathbf{D}_\mu \mathbf{F}^{\mu\nu}] = \mathbf{J}^\nu[\rho]$

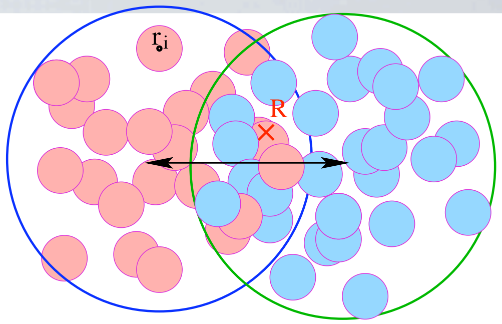
(Suplemented by JIMWLK evolution)

-Other approaches: Breakdown of hypothesis of independent particle production from different nucleons, energy-dependent momentum cutoffs in event generators, resummation of multiple scatterings (coherent and incoherent)....

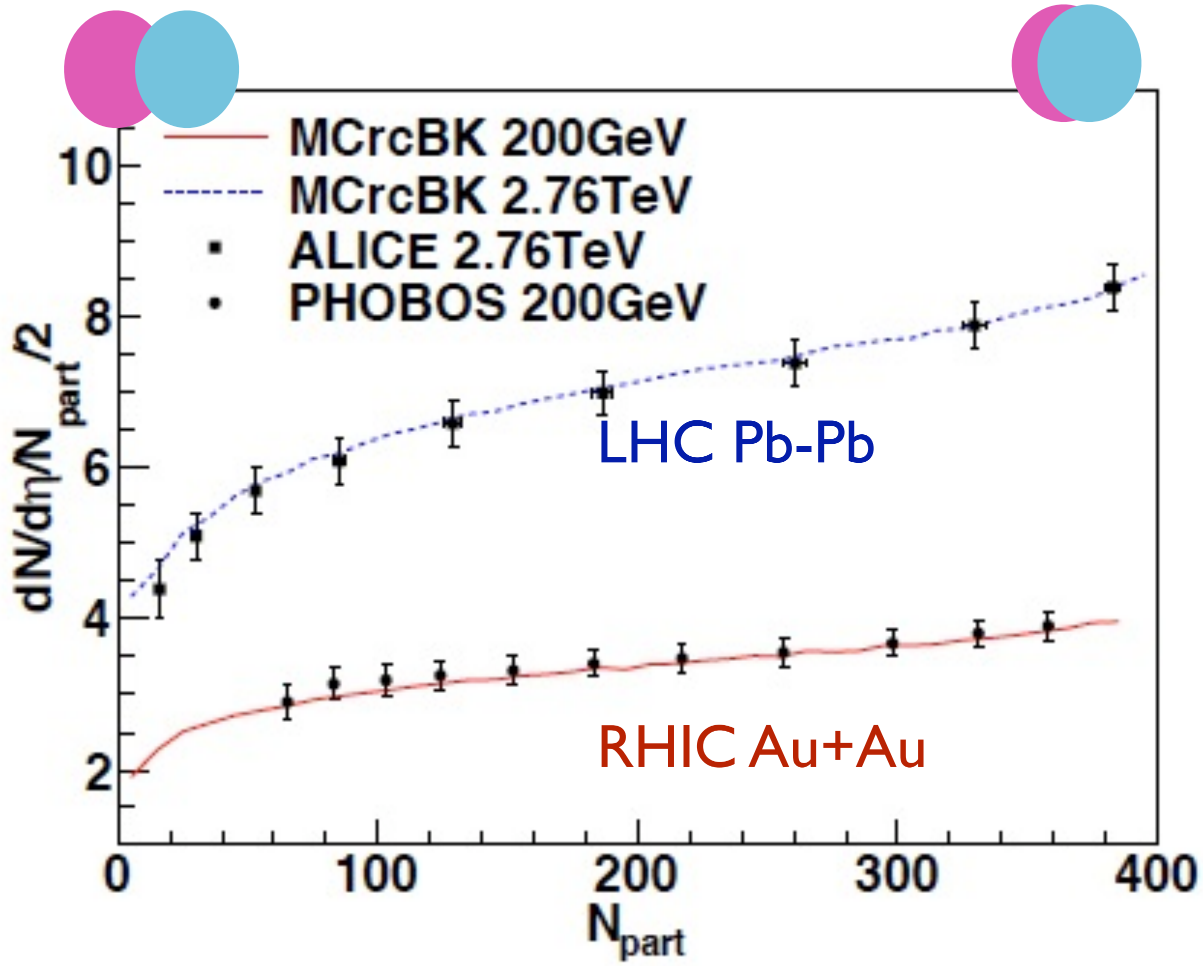
Modeling the initial state of HIC

- In the CGC, multiplicities rise proportional to the (local) saturation scale

$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s}^{0.3}\, N_{part}$$



- Approximate factorization of energy and geometry dependence. Good description of RHIC and LHC data



Modeling the initial state of HIC

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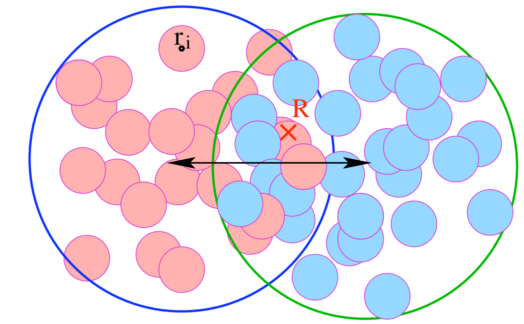
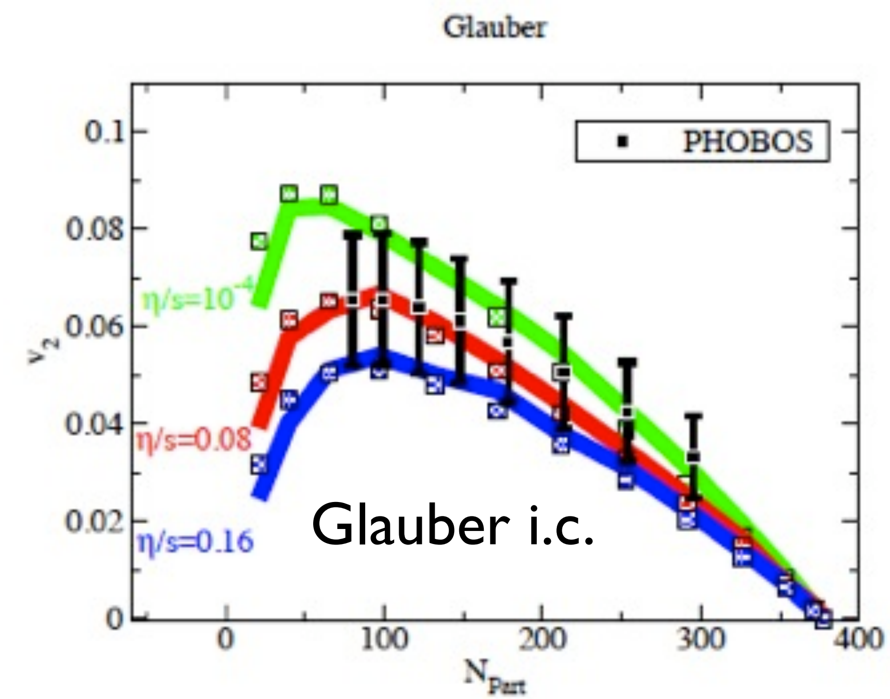


$$\left.\frac{\mathbf{dN^{gluons}}}{\mathbf{d\eta\, d^2b}}\right|_{\eta=0} \propto \mathbf{Q_s^2(\sqrt{s}, b)} \sim \mathbf{\sqrt{s}^{0.3}\, N_{part}}$$

• Approximate factorization of energy and geometry dependence. Good description of RHIC and LHC data

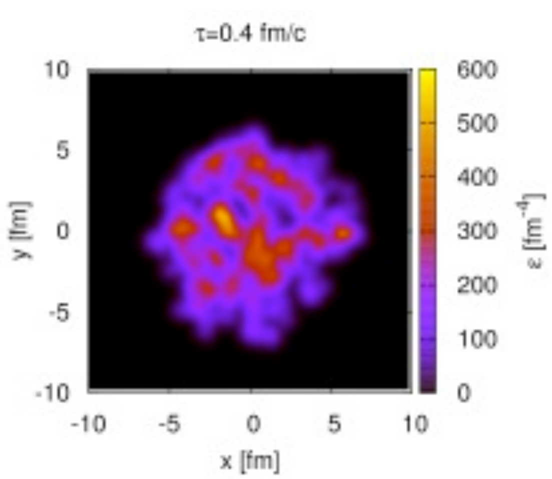
• Accurate modeling of the transverse initial energy densities is crucial for the extraction of transport parameters!!

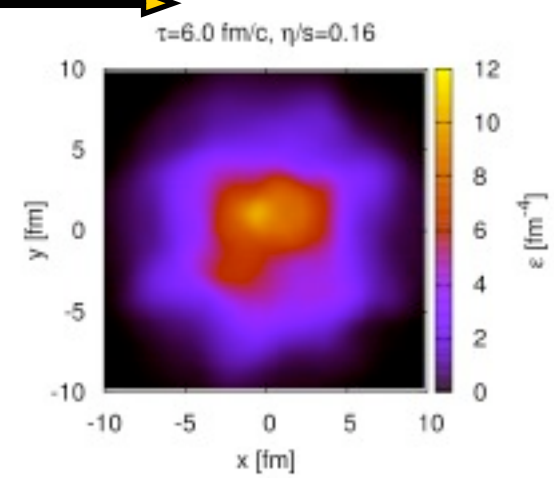


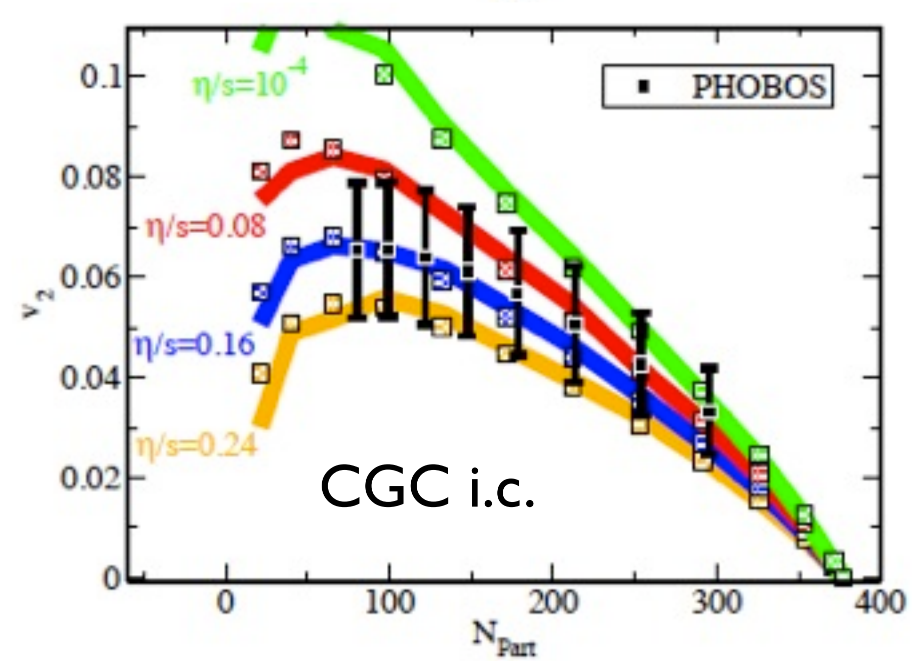
INITIAL (t~0.4 fm)

TRANSPORT (HYDRO)

FINAL (t~6 fm)







Fluctuations: Geometric (nucleon positions)
Negative binomial (subnucleon level)
Others?

Modeling the initial state of HIC

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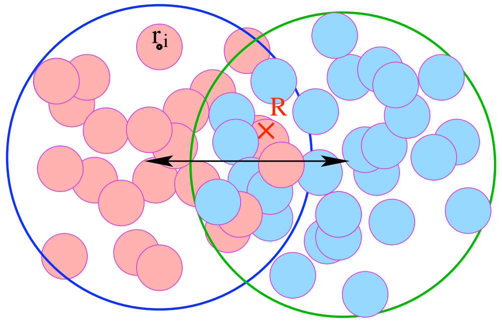
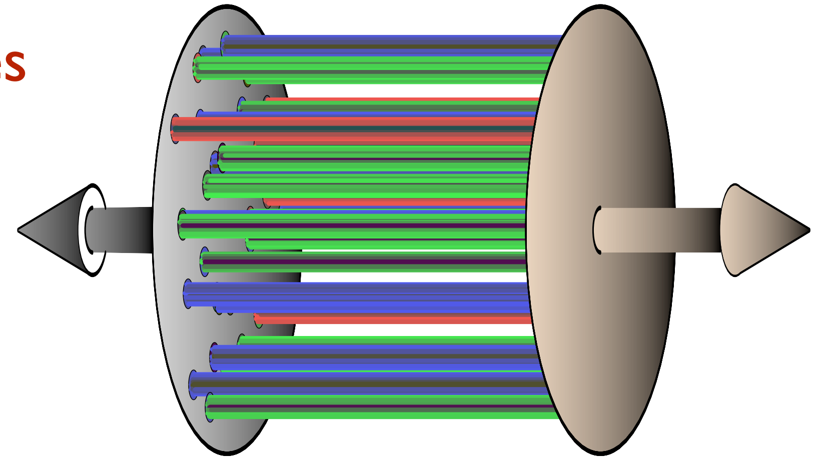
$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s}^{0.3}\, N_{part}$$

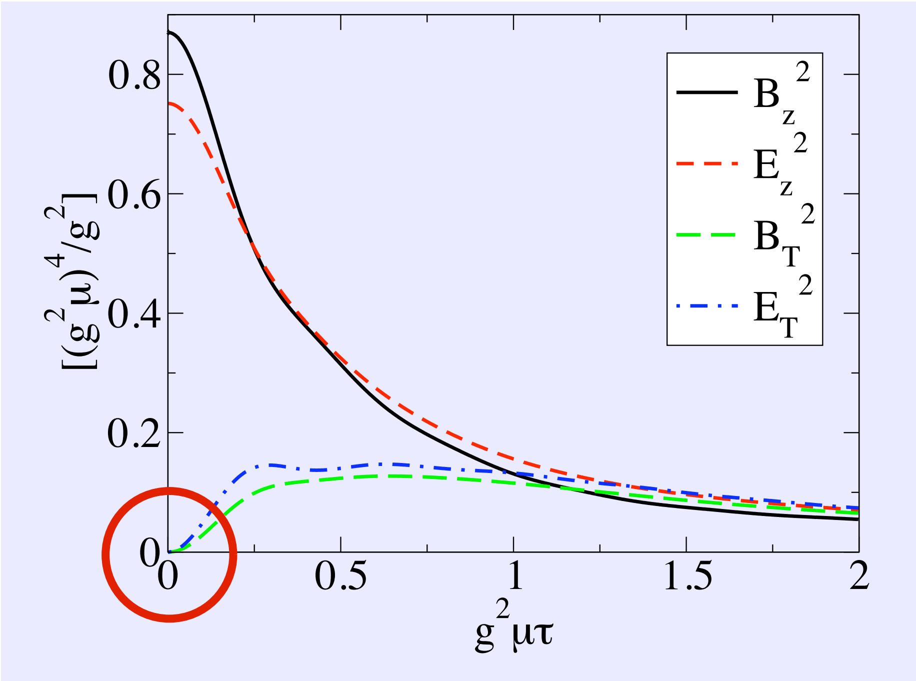


- Color electric-magnetig fields after the collision are purely longitudinal: Flux Tube picture

Flux tubes

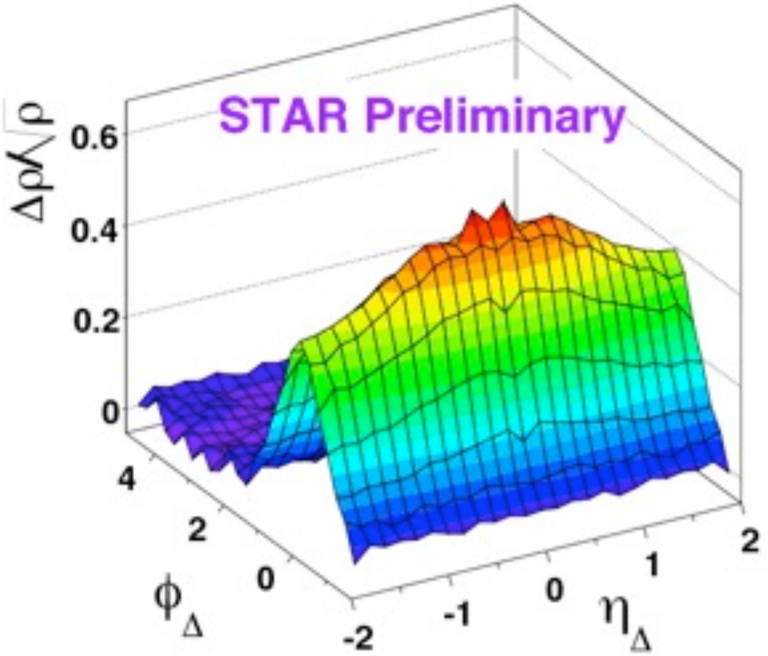


$$\boldsymbol{E}^z = ig\left[\mathcal{A}_1^i, \mathcal{A}_2^i\right] \quad , \qquad \boldsymbol{B}^z = ig\epsilon^{ij}\left[\mathcal{A}_1^i, \mathcal{A}_2^j\right]$$

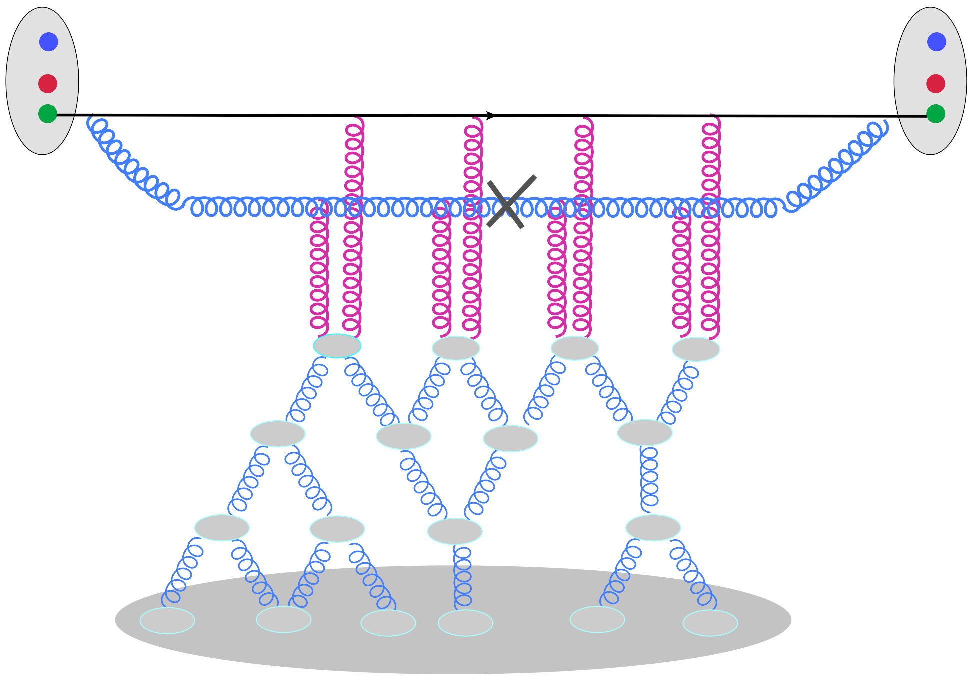


Correlation length in the transverse plane: $\Delta r_\perp \sim 1/Q_s(x)$

Correlation length in rapidity $\Delta\eta \sim 1/\alpha_s$



Inclusive particle production in p+Pb collisions at the LHC



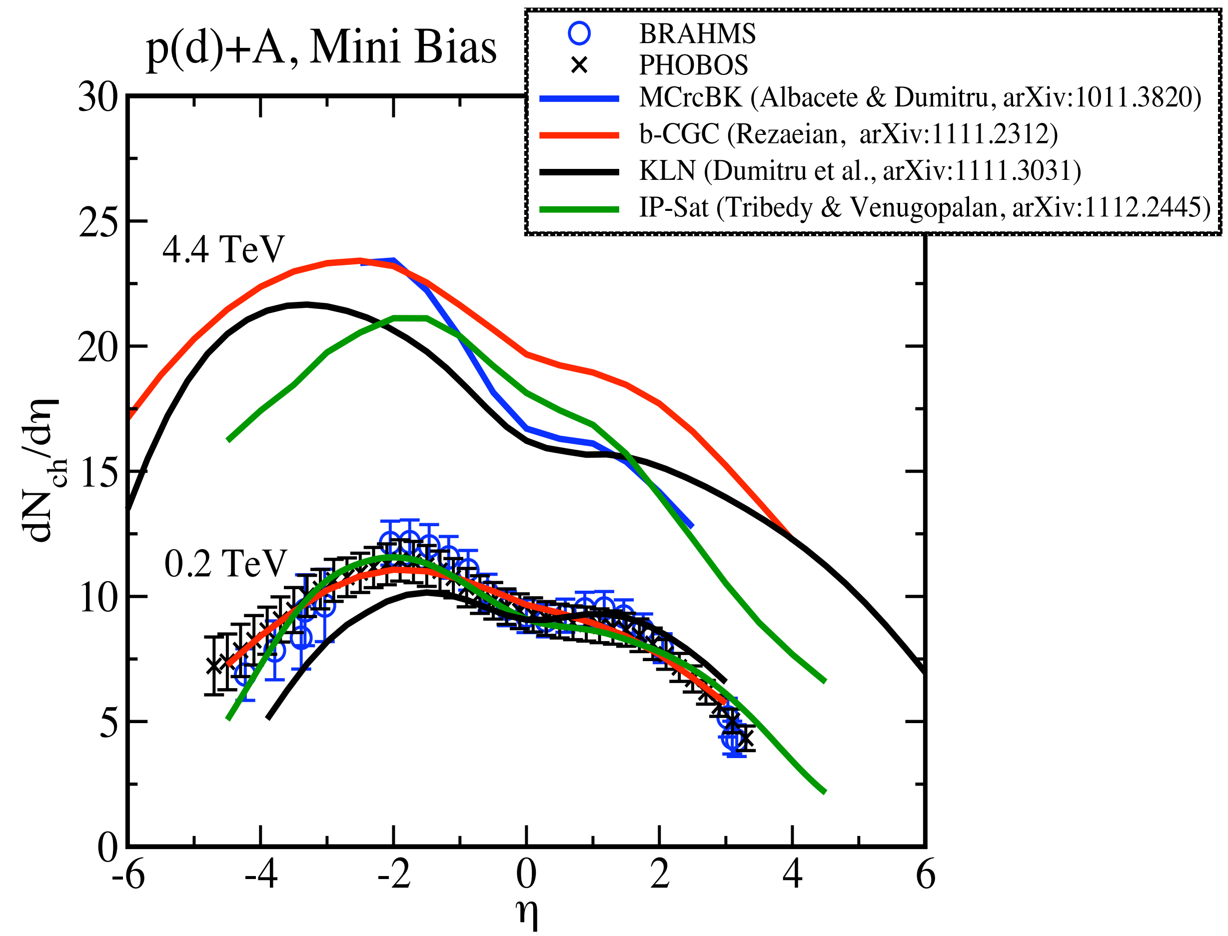
Kt-factorization: $x_1 \ll$

$$\frac{dN^g}{dy_h d^2k_t} \approx \frac{\alpha_s C_F}{k_t^2}\, \phi_p(x_1, k_t) \otimes \phi_A(x_2, k_t)$$

Hybrid formalism: $x_1 \gg$

$$\frac{dN^g}{dy_h d^2k_t} \approx x q(x_1, k_\perp) \otimes \phi_A(x_2, k_t)$$

$$x_{1(2)} = \frac{k_t}{\sqrt{s}} e^{\pm y_h}$$



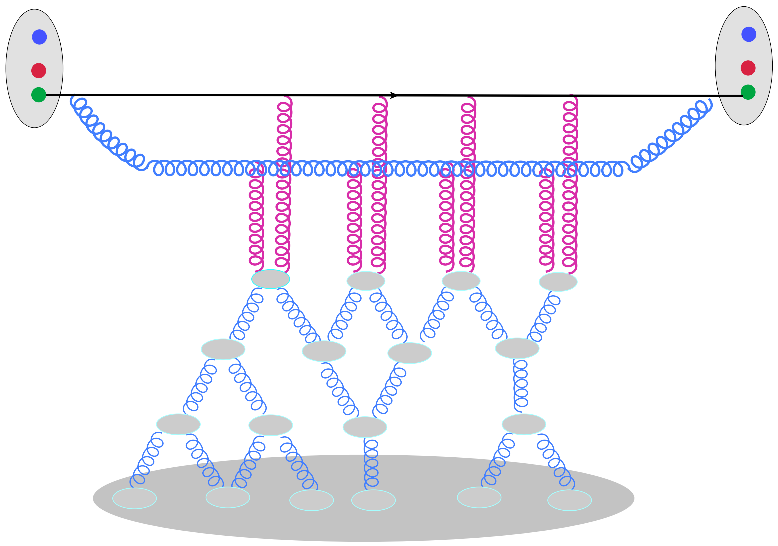
Overall, different CGC works predict

$$\left.\frac{dN^{ch}_{pPb}}{d\eta}\right|_{\eta=0} (5\,\mathrm{TeV}) \sim 17 \pm 2$$

we'll know the answer very soon!!

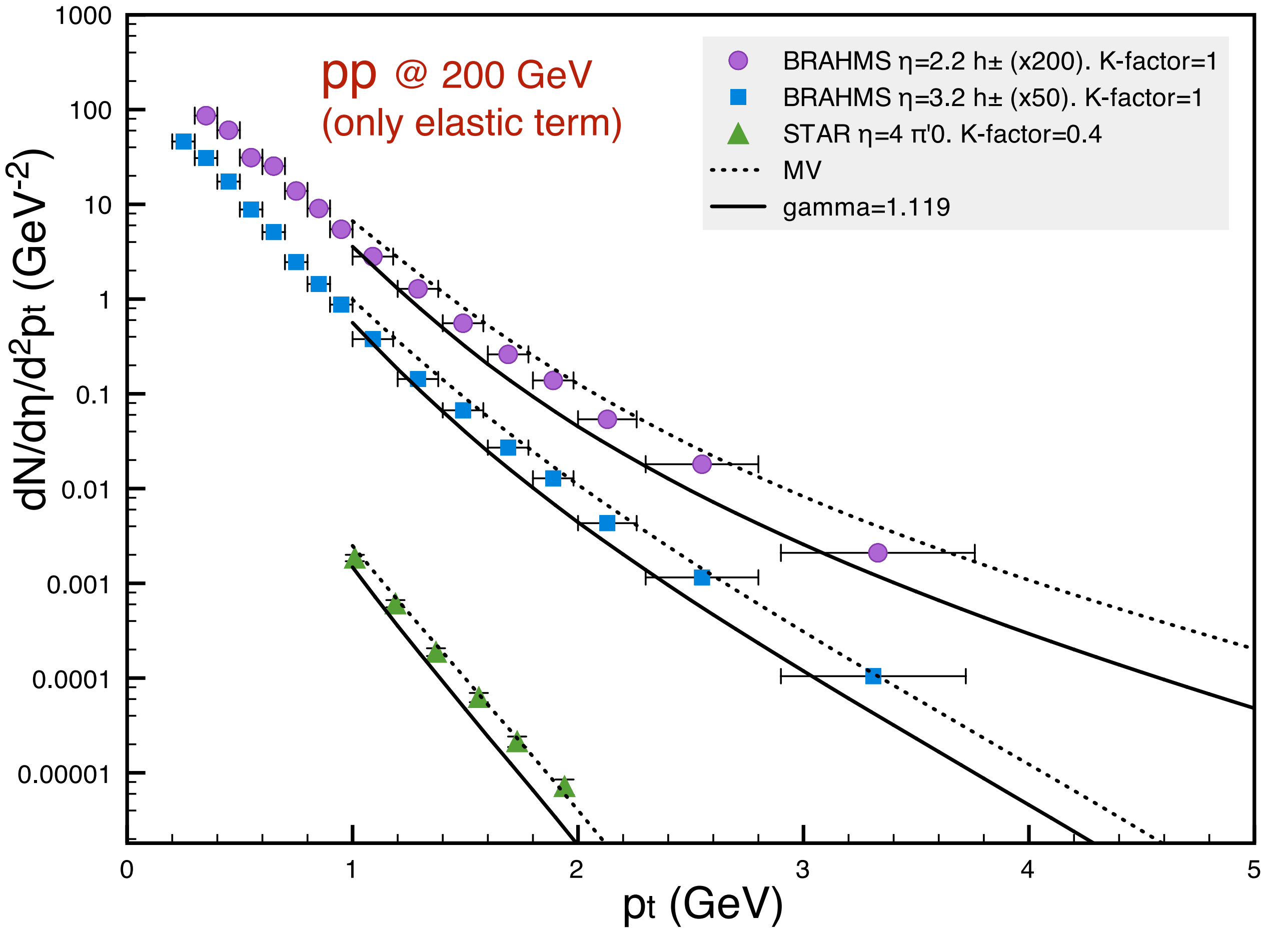
Calibrating the CCG in p+Pb collisions at the LHC

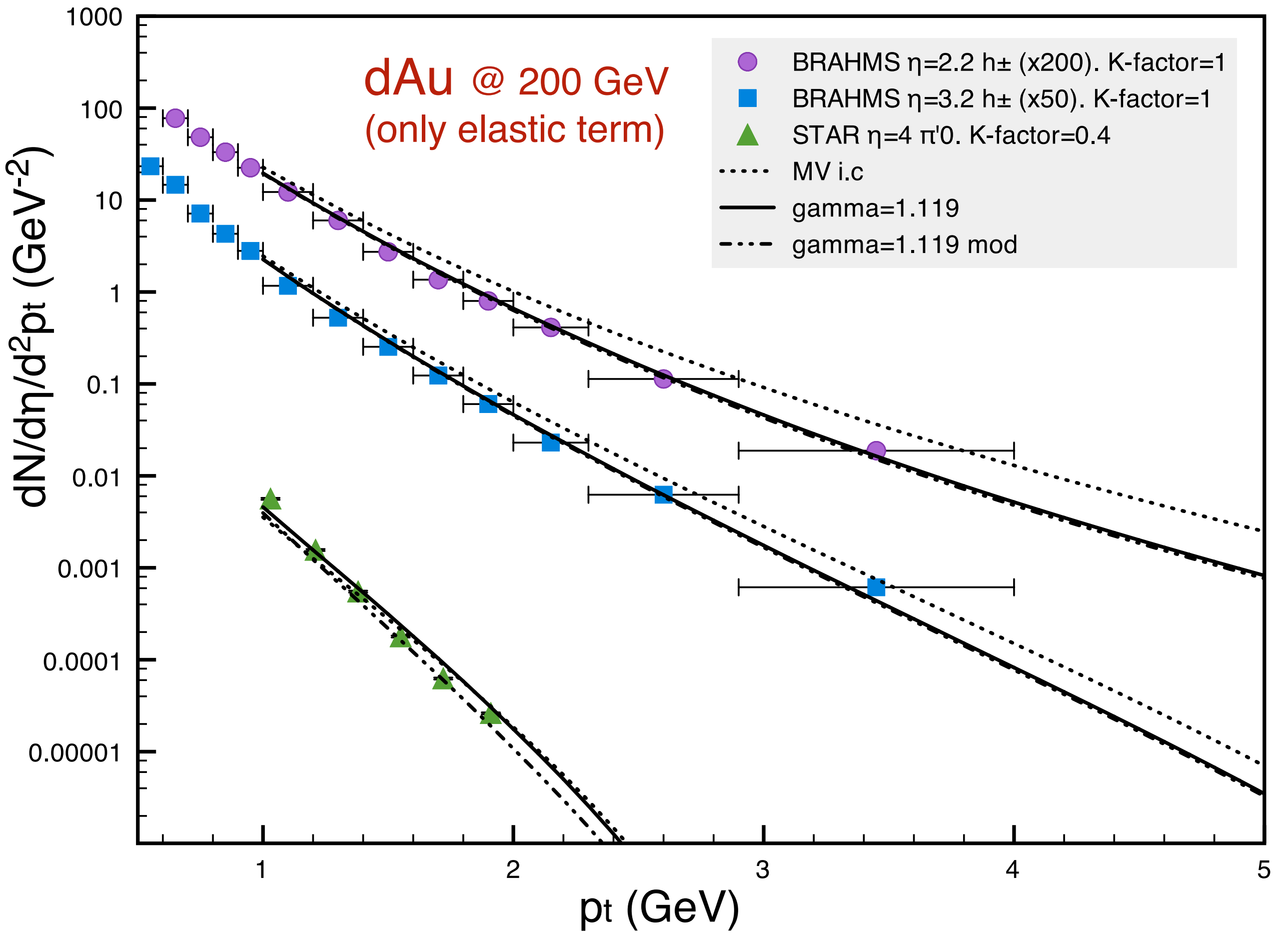
- Inclusive particle production



$$\frac{dN^g}{dy_h d^2k_t} \approx xq(x_1, k_\perp) \otimes \phi_A(x_2, k_t) \qquad x_{1(2)} = \frac{k_t}{\sqrt{s}} e^{\pm y_h}$$

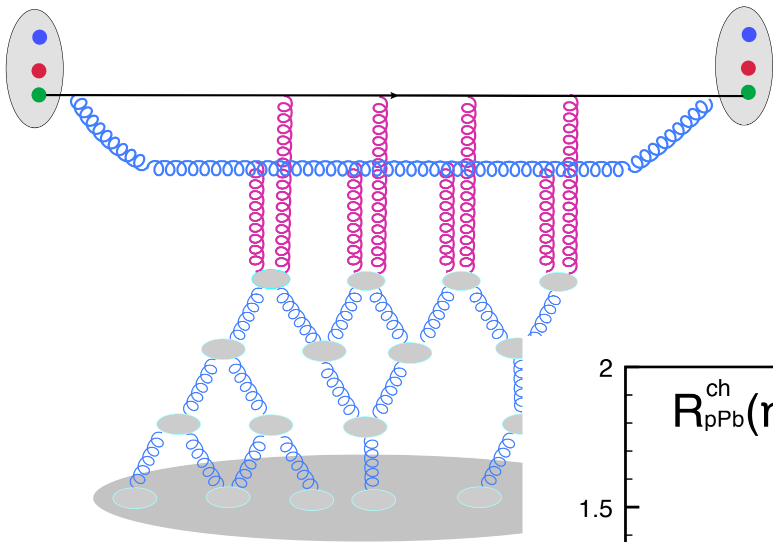
- Good description of RHIC forward single inclusive yields
- However:
  - K-factors ~0.3 needed at most forward rapidities: large-x effects
  - RHIC data does not constrain much the i.c. for BK evolution





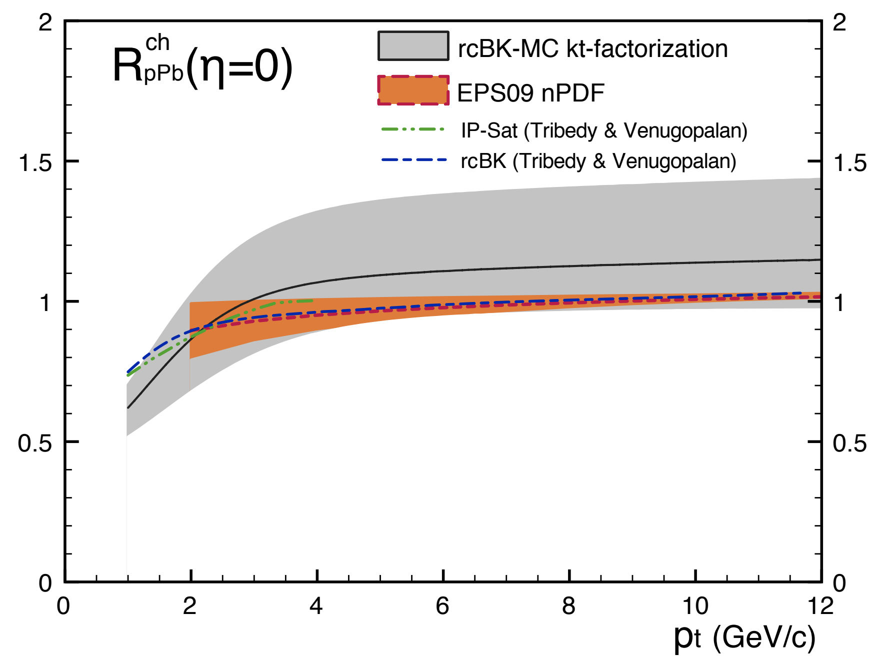
Calibrating the CCG in p+Pb collisions at the LHC

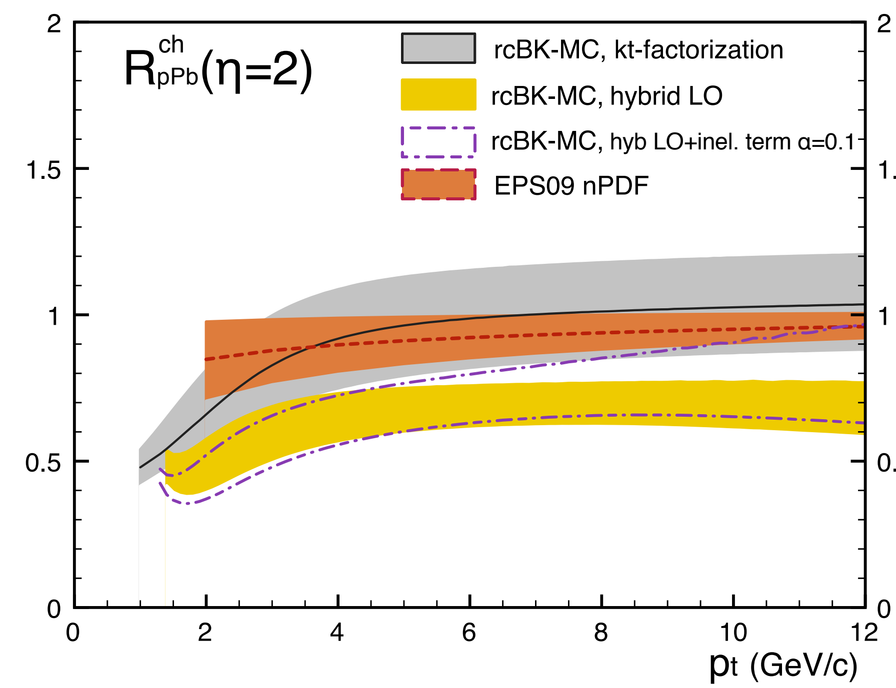
- Inclusive particle production

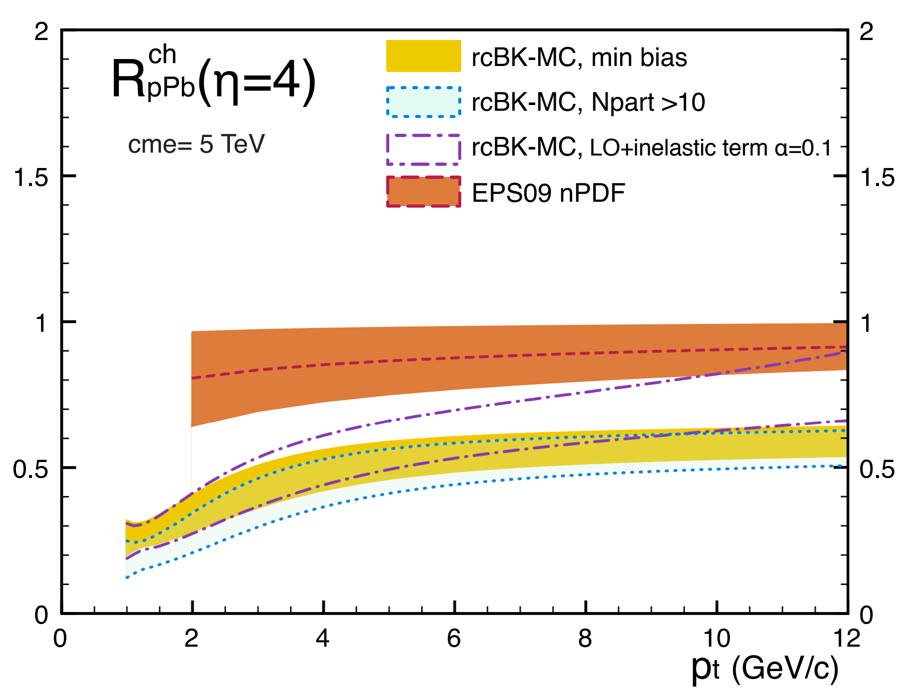


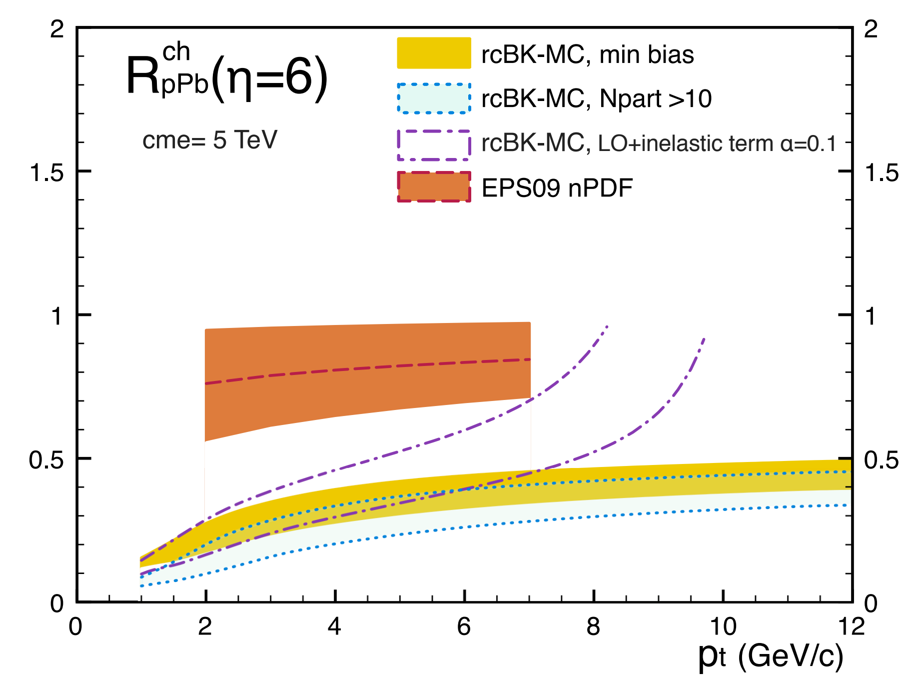
- Nuclear modification factors at the LHC: Testing non-linear evolution

$$R_{pA} = \frac{\frac{dN^h_{pA}}{dy_h d^2k_\perp}}{A^{1/3}\frac{dN^h_{pp}}{dy_h d^2k_\perp}} \sim \frac{\phi_A(x, k_\perp^2)}{A^{1/3}\phi_p(x, k_\perp^2)}$$

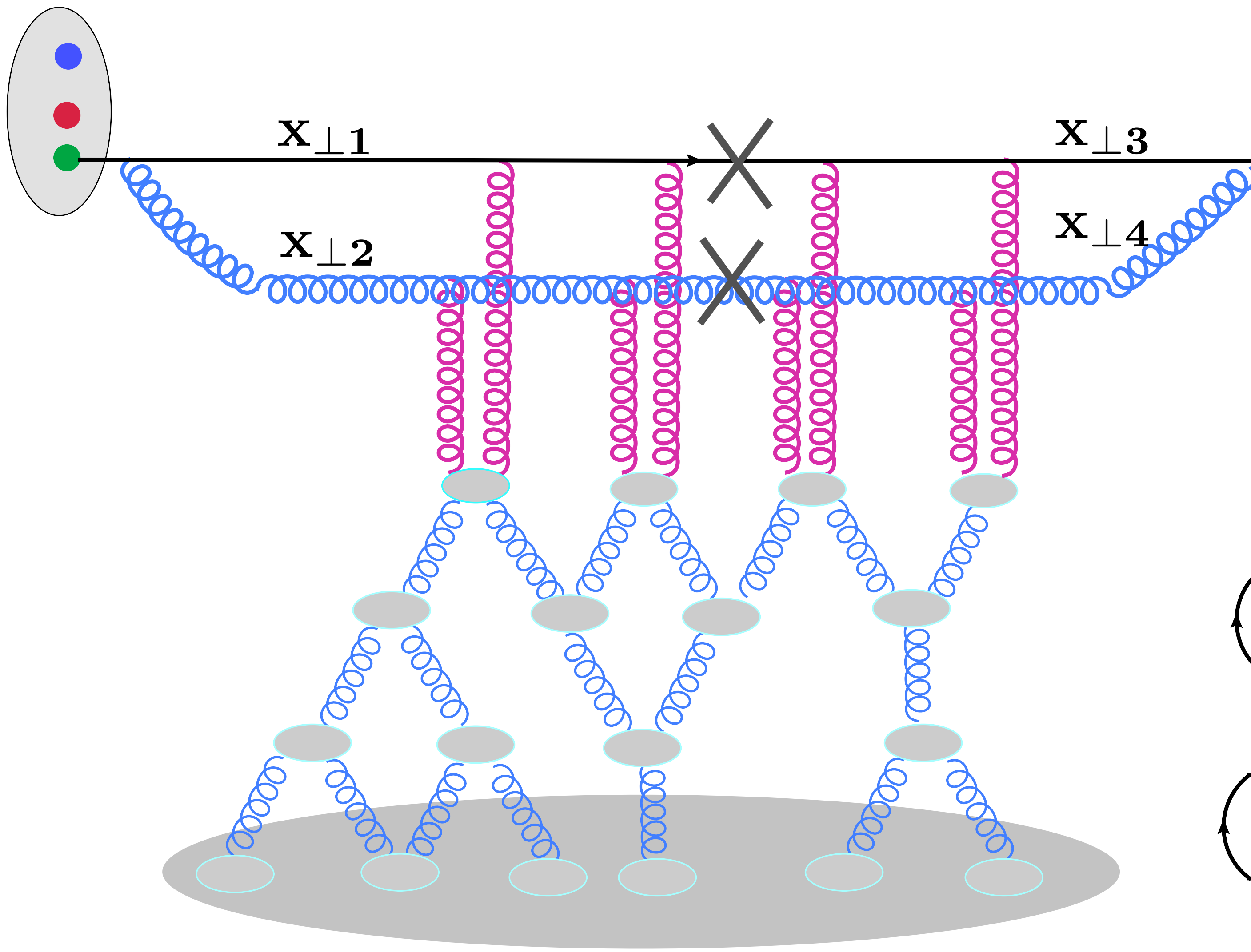


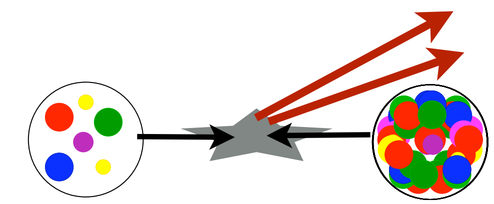




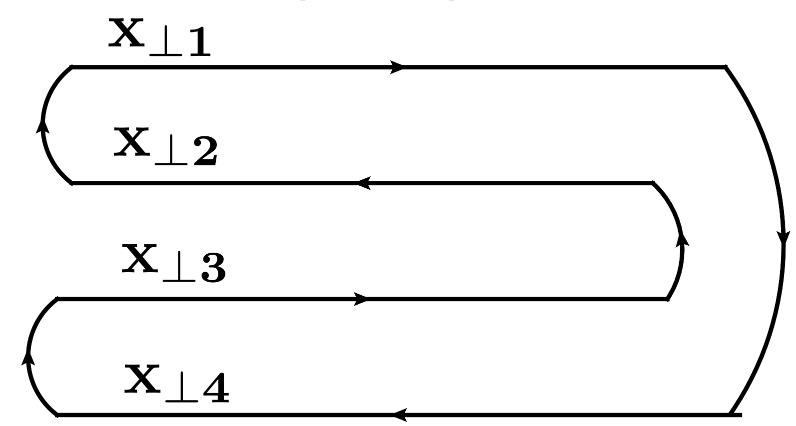


Double inclusive production in pPb collisions





quadrupole

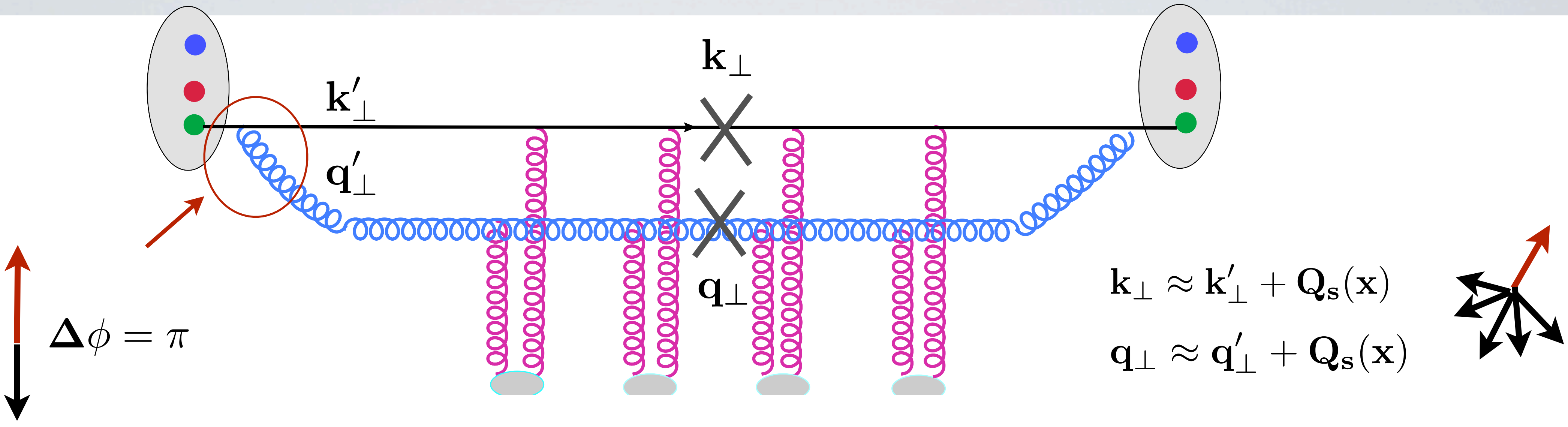


More exclusive observables involve the knowledge of higher n-point functions:

$$\frac{dN^{q\to qg}}{dy_{h1}dy_{h2}d^2k_t d^2q_t} \sim \langle \mathrm{tr}\left[V(x_{\perp 1})V^\dagger(x_{\perp 2})V(x_{\perp 3})V^\dagger(x_{\perp 4})\right]\rangle_x + \ldots$$

... which requires solving the JIMWLK equation. Solving the BK-equation for the 2-point function is not enough

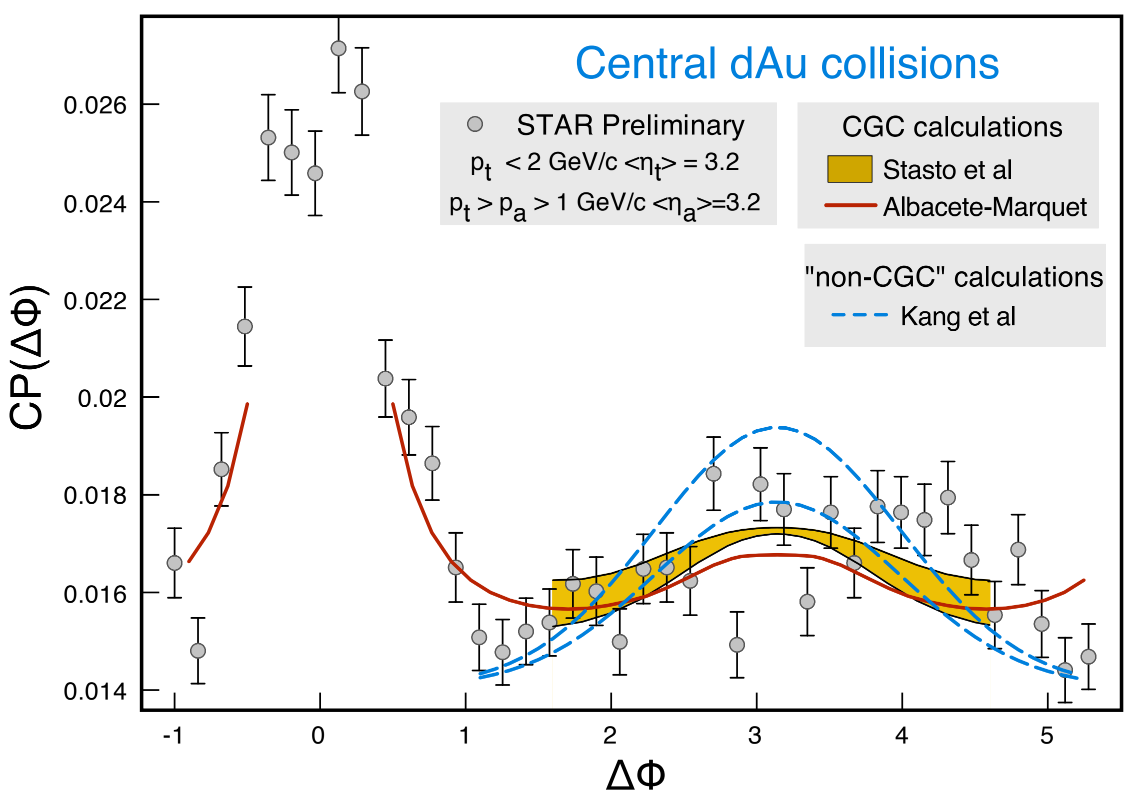
Angular decorrelation of forward di-hadrons

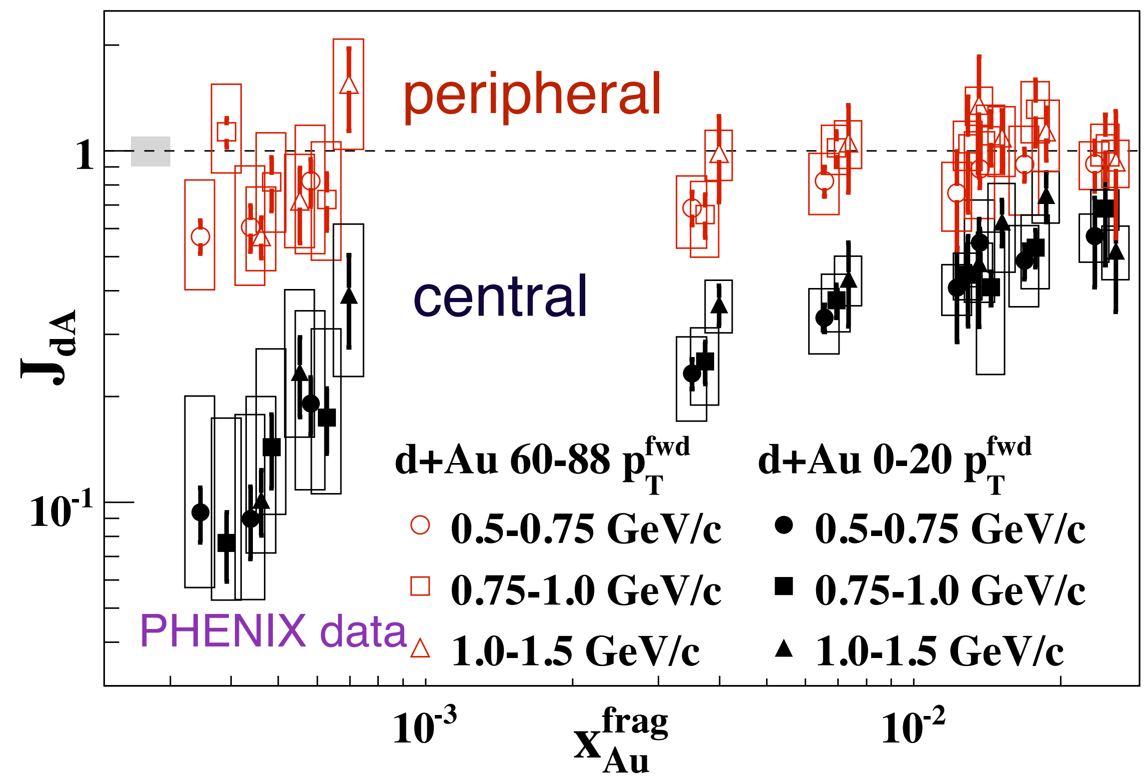


$$\mathbf{k}_\perp \approx \mathbf{k}'_\perp + \mathbf{Q_s}(\mathbf{x})$$
$$\mathbf{q}_\perp \approx \mathbf{q}'_\perp + \mathbf{Q_s}(\mathbf{x})$$

Angular decorrelation happens if $(\mathbf{k}'_\perp, \mathbf{q}'_\perp) \sim \mathbf{Q_s}(\mathbf{x})$

$$J_{dA} = I_{dA} \times R^t_{dA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{\sigma^{\rm pair}_{dA}/\sigma_{dA}}{\sigma^{\rm pair}_{pp}/\sigma_{pp}}$$

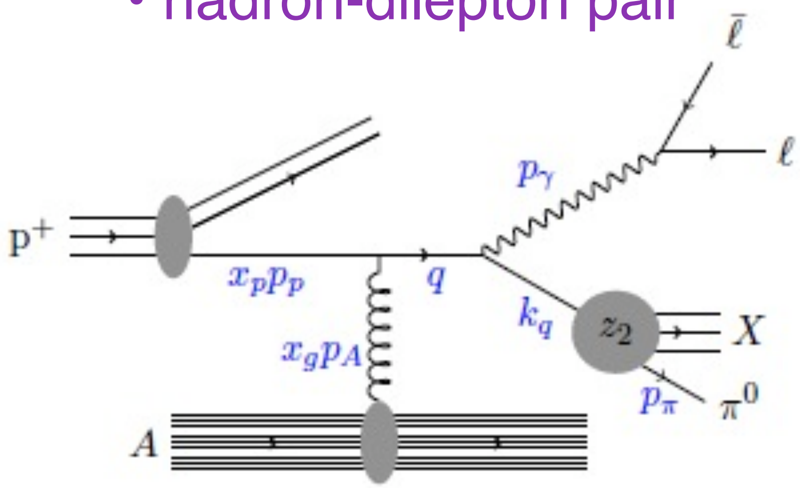




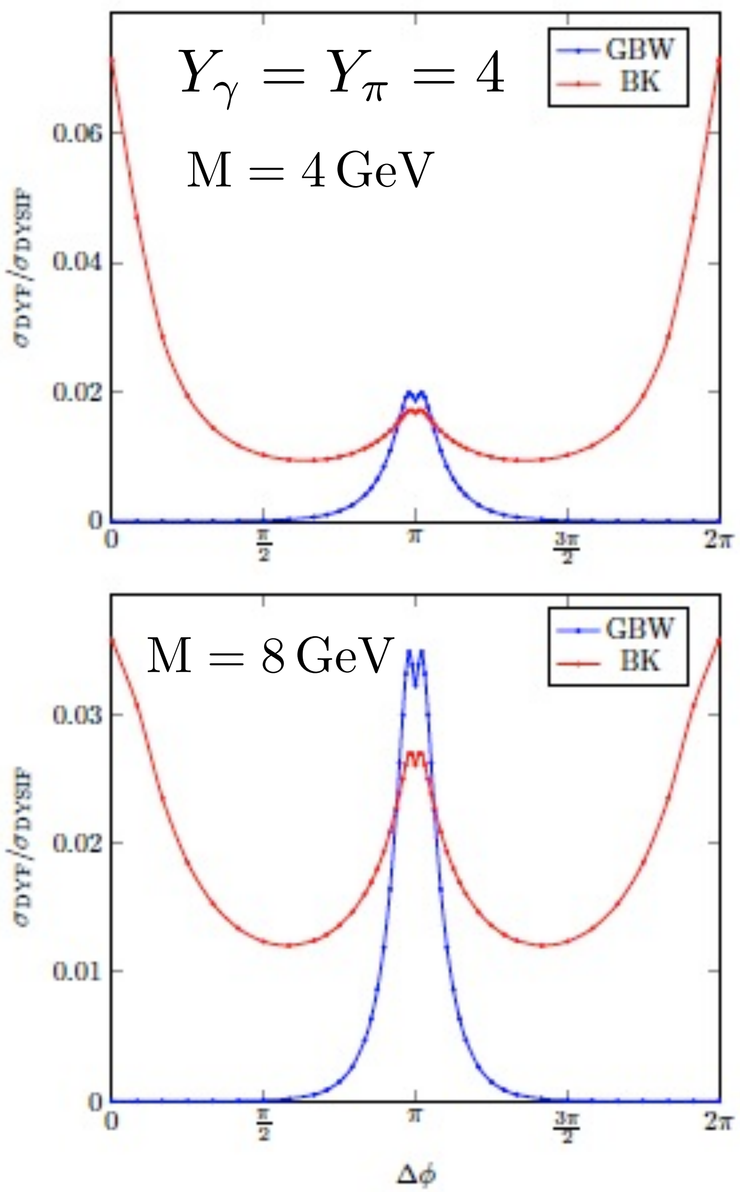
- Need for a better description of n-point functions.
- Better determination of the pedestal: K-factors in single inclusive production? Role of double parton scattering?
- WARNING: Alternative explanations based on higher twist expansion are also possible

hadron-photon* correlations in pPb collisions at the LHC

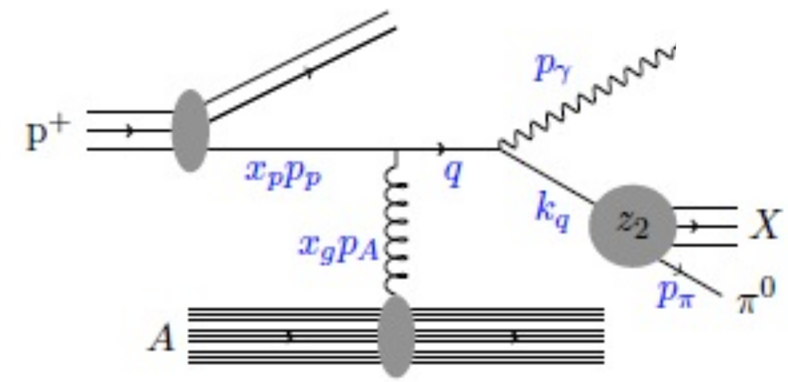
- hadron-dilepton pair



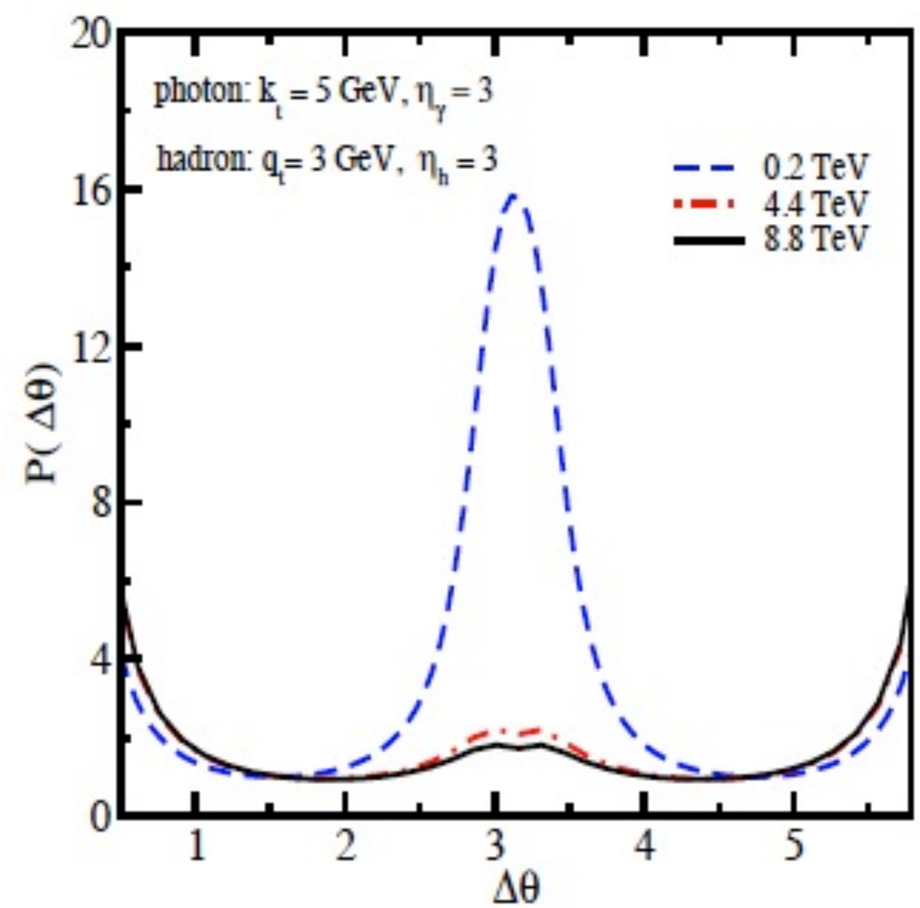
Stasto et al



- hadron-photon



Jalilian-Marian et al



These processes are theoretically cleaner:
Only knowledge of 2-point needed!!

Outlook

✔ Important steps have been taken in promoting GCG to an useful quantitative tool
- Continuos progress on the theoretical side
- Phenomenological effort to systematically describe data from different systems (e+p, e+A, p+p, d+Au, Aa+Au and Pb+Pb) in an unified framework

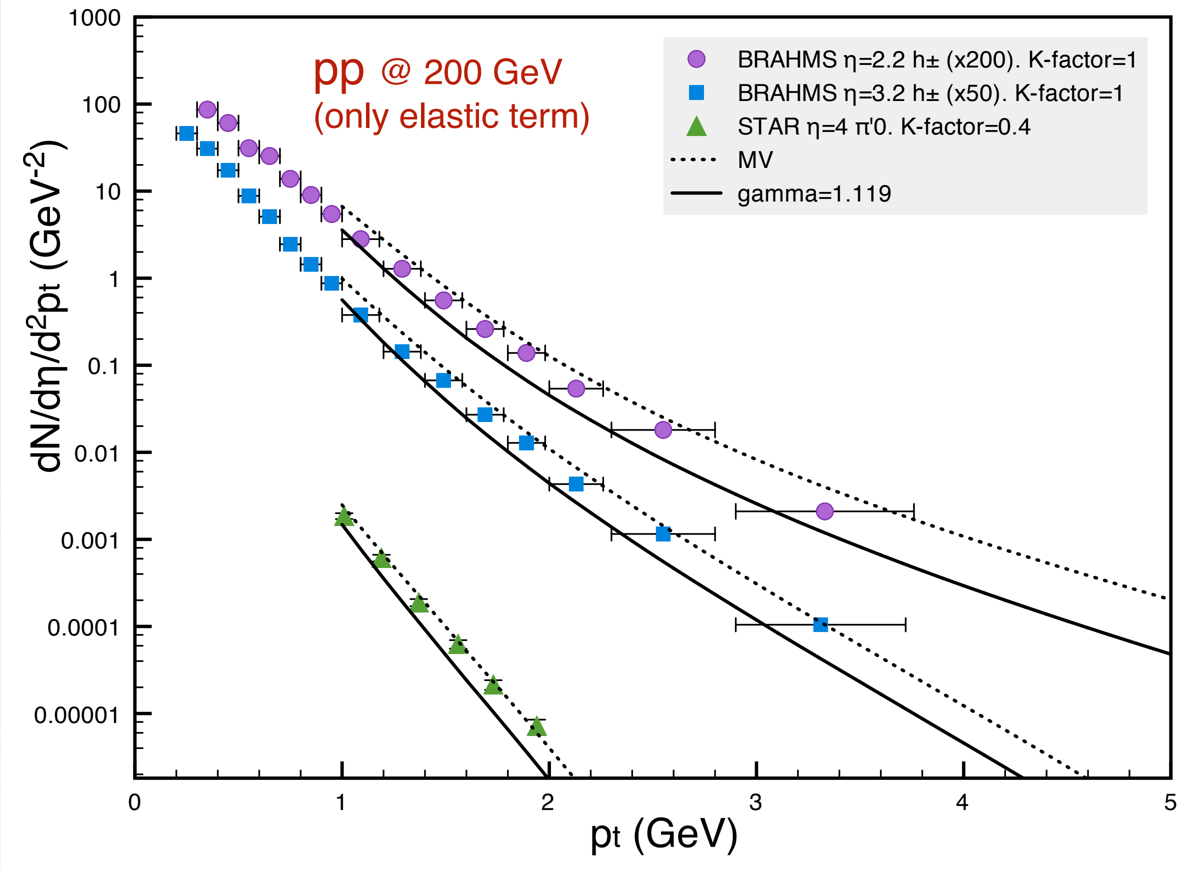
✔ Most solid CGC predictions for the upcoming p+Pb run:
- Suppression of nuclear modification factors at moderate pt already at mid-rapidity
- Stronger suppression at more forward rapidities (evolution)
- Suppression of di-hadron and photon-hadron angular correlations

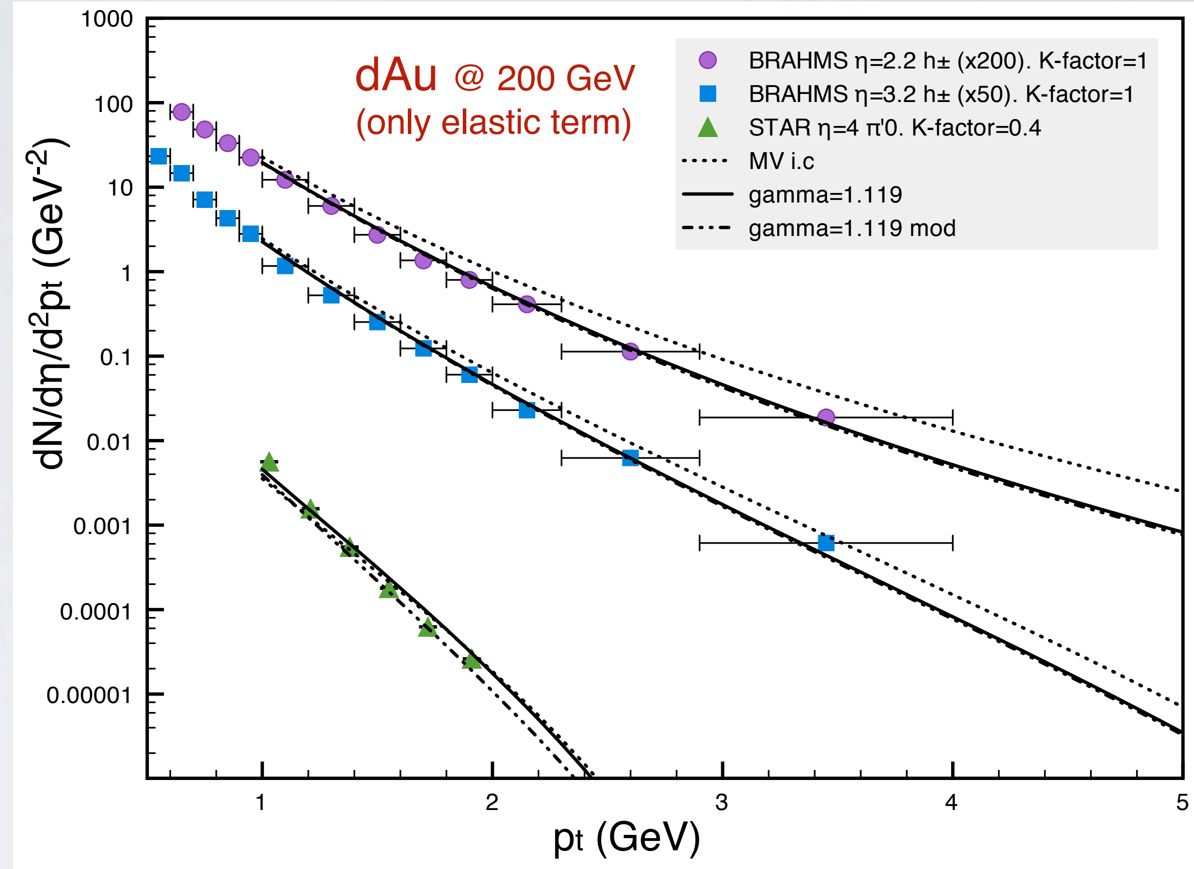
✔ Current predictions carry some uncertainty due to lack of data to constrain NP aspects of nuclear UGD. This problem can be largely fixed through the measurement of simple observables (i.e. single inclusive spectra) in p+Pb collisions

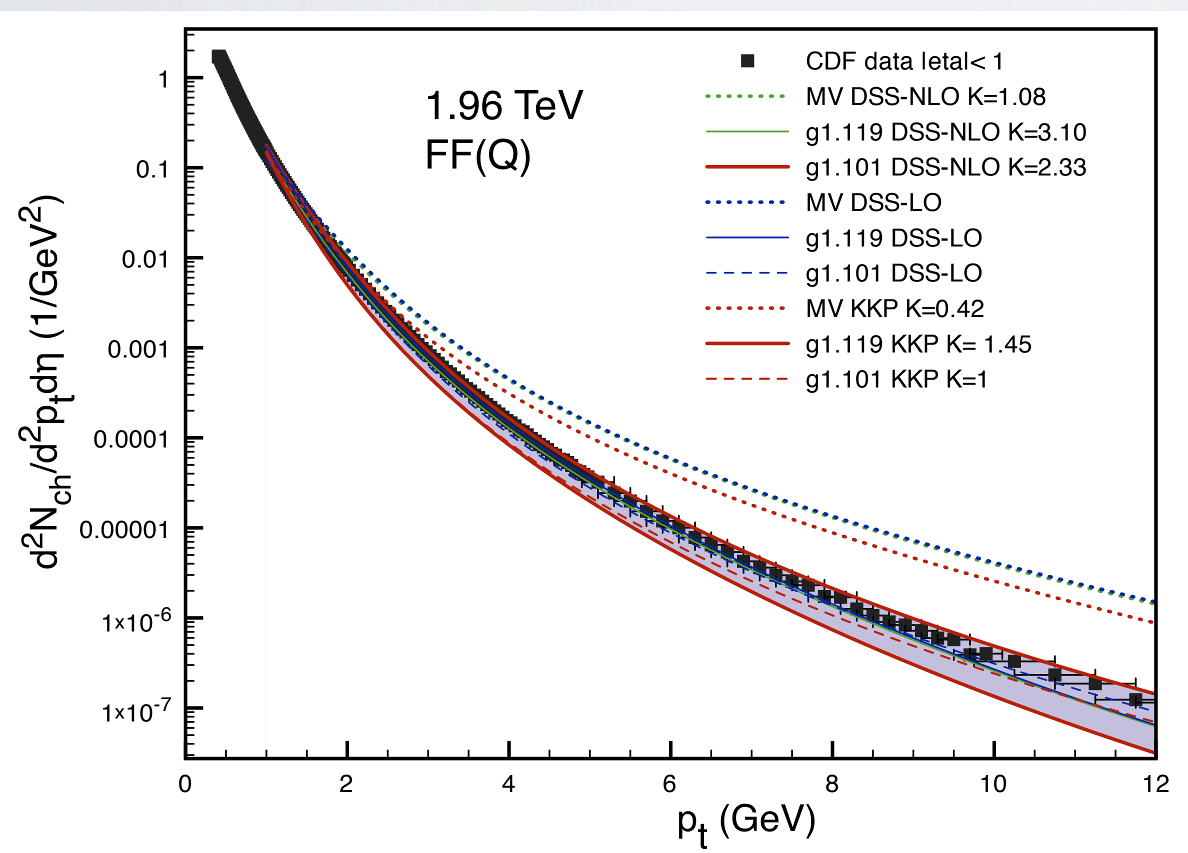
✔ Our knowledge of the CGC effective theory and of coherence effects in HIC in general will be largely improved by the upcoming p+Pb data at the LHC

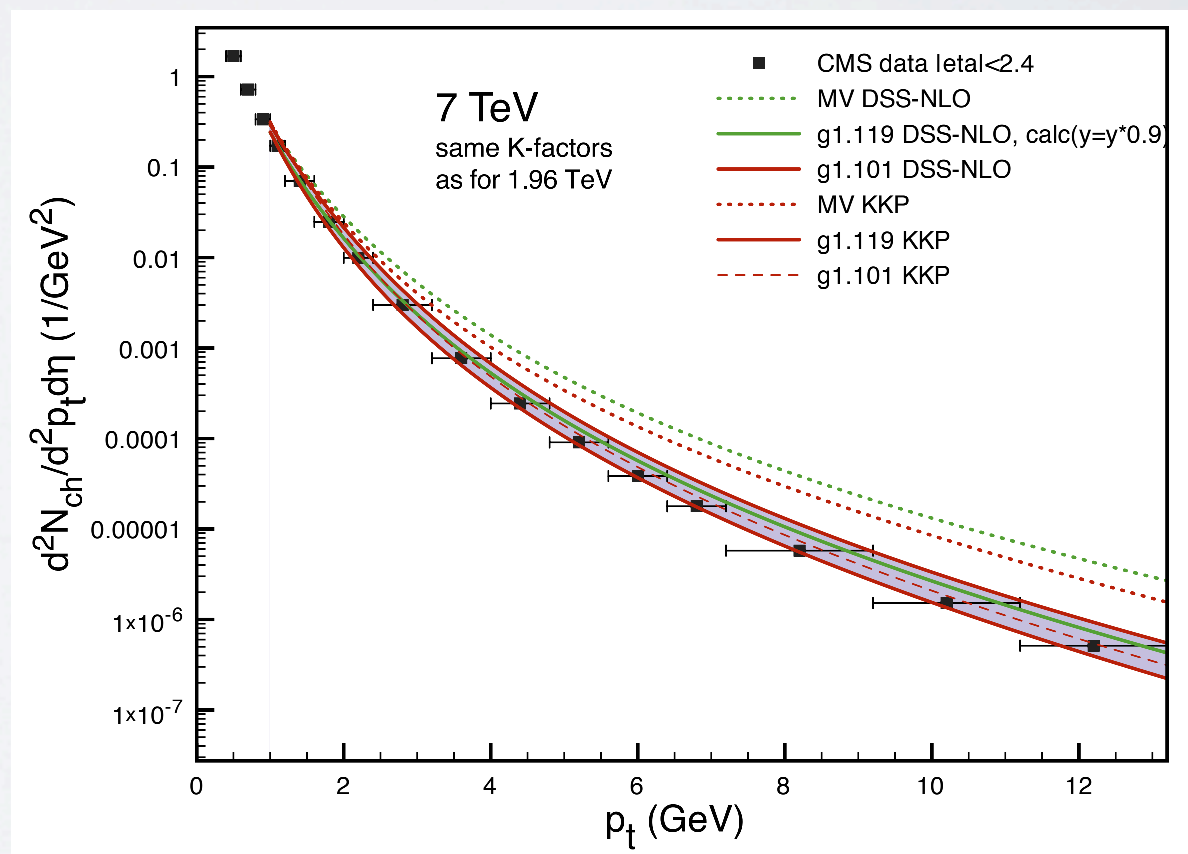
GRAZIE!

Back up slides









Back up slides